Filter Design With SMR(Solidly Mounted Resonator)Resonator

Dissertation submitted to
Visvesvaraya National Institute of Technology, Nagpur
In partial fulfillment of the requirements for the award of the degree

Master of Technology
in
VLSI Design

by

Abdul Basheer
(MT23MVD011)

Under the guidance of

Prof. Rajendra M. Patrikar

Centre for VLSI and Nanotechnology
Visvesvaraya National Institute of Technology
Nagpur 440010 (India)

June 2025

Filter Design With SMR(Solidly Mounted Resonator)Resonator

Dissertation submitted to
Visvesvaraya National Institute of Technology, Nagpur
In partial fulfillment of the requirements for the award of the degree

Master of Technology
in
VLSI Design

by

Abdul Basheer
(MT23MVD011)

Under the guidance of

Prof. Rajendra M. Patrikar

Centre for VLSI and Nanotechnology
Visvesvaraya National Institute of Technology
Nagpur 440010 (India)

June 2025

©Visvesvaraya National Institute of Technology, Nagpur 2025

Centre for VLSI and Nanotechnology
Visvesvaraya National Institute of Technology, Nagpur

DECLARATION

I, **Abdul Basheer**, hereby declare that this dissertation titled **"Filter Design With SMR(Solidly Mounted Resonator)Resonator"** is carried out by me in the **Center for VLSI and Nanotechnology** of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier whole or in part for the award of any degree/diploma at this or any other Institution / University.

Abdul Basheer
Date:

CERTIFICATE

This is to certify that the dissertation titled **"Fiter Design With SMR(Solidly Mounted Resonator)Resonator"** is submitted by **Abdul Basheer (MT23MVD011)** in partial fulfillment of the requirements for the award of **Master of Technology in VLSI Design,** VNIT Nagpur. The work is comprehensive, complete and fit for final evaluation.

Prof. R. M. Patrikar
Centre for VLSI and Nanotechnology
VNIT, Nagpur.

Prof. Sanjay B. Dhok
Head, Centre for VLSI and Technology
VNIT, Nagpur
Date:_____

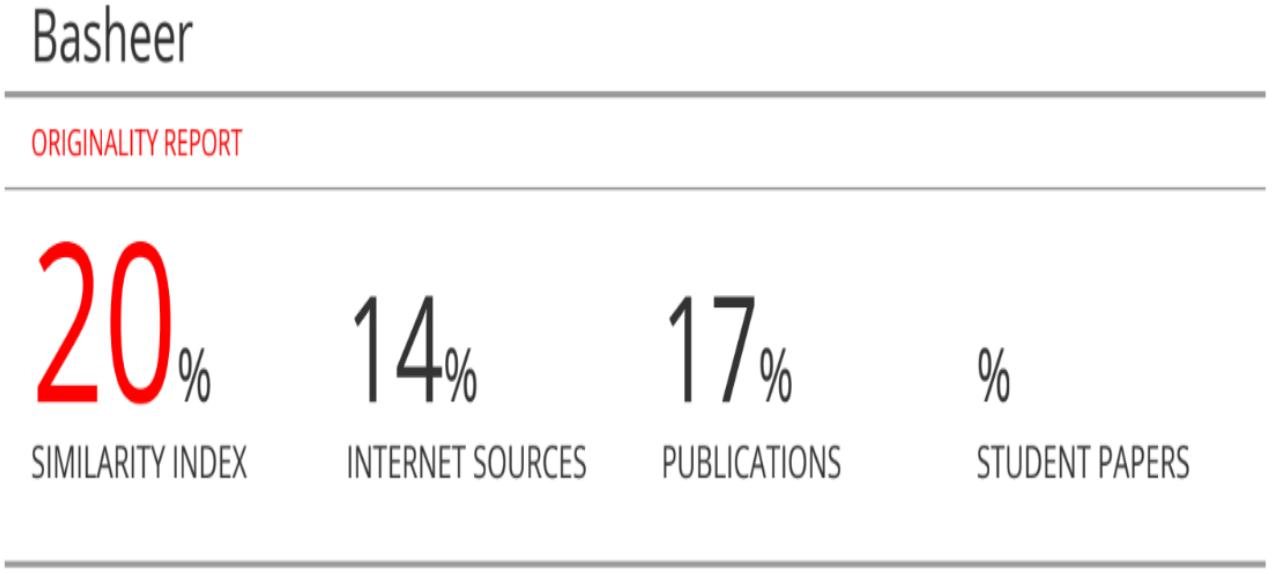
Center for VLSI and Nanotechnology
Visvesvaraya National Institute of Technology, Nagpur

June 2025

Date:_____

Non-Plagiarism Certificate

Certified that M. Tech Dissertation titled **"Filter Design With SMR (Solidly Mounted Resonator) Resonator"** submitted by **Abdul Basheer (MT23MVD011)** has been checked for plagiarism using TURNITIN software and the overlap is found within prescribed limits. A summary of the report is given below



Abdul Basheer
Date:_____

Prof. R. M. Patrikar
Supervisor

ACKNOWLEDGEMENT

I want to begin by sincerely thanking my mentor, Prof. Rajendra M. Patrikar, for his unwavering encouragement, patience, and support during this trip. He allowed me to explore freely, yet he was always there to help me find my way when I needed it. His mentoring has taught me a lot, not only technically but also how to approach research with discipline and curiosity.

Our department head, Prof. S. B. Dhok, has my sincere gratitude for his support and for fostering a supportive learning atmosphere. I want to express my sincere gratitude to Prof. R. B. Deshmukh, Dr. G. C. Patil, Dr. Vasu Pulijala, and Dr. Nikhil Deep Gupta for their insightful comments and suggestions during my study. Their recommendations really enhanced the caliber of my work and allowed me to view things from new angles.

I also want to thank the Institute's director, Prof. P. L. Patel; academic dean, Prof. V. R. Kalamkar; and associate dean, Prof. R. V. Taiwade, for their unwavering support and dedication to creating an academic environment that encourages students to achieve. Their guidance and assistance have been crucial in supplying the materials and motivation required to finish this endeavor.

Lastly, I want to express my sincere gratitude to my family and friends. Throughout this road, their constant belief in me, words of encouragement, and unfailing support made a big difference. Their presence gave me the equilibrium and inspiration I needed to remain focused and upbeat during stressful or uncertain times.

Abdul Basheer

ABSTRACT

The rapid development in technology of wireless and communication systems have resulted to technology innovation in the performance of the component and compatibility with complementary metal-oxide semiconductor(CMOS) fabrication technology, and improvement in the system to satisfy requirement for quicker signal processing, in terms of cost-effectiveness, miniaturization of chip, and reduce power consumption. The requirement for the high performance and reliable resonator with low motional impedance and higher quality factor are increasing. In a radio frequency (RF) electromechanical resonator, reducing motional resistance to a minimum is critical for the device's direct interface with low-power 50ohm electronics. Piezoelectric MEMS resonator can fulfill all these needs.

Solidly Mounted Resonators (SMRs) have emerged as a critical component in RF filter design, offering high performance, compact size, and compatibility with standard semiconductor processes. This paper presents the design, simulation, and analysis of an RF bandpass filter based on SMR technology, targeting wireless communication applications. The SMR structure employs a piezoelectric thin film, typically AlN or ZnO, sandwiched between metal electrodes and acoustically isolated from the substrate using a Bragg reflector. This configuration enables efficient acoustic wave confinement, resulting in high Q-factors and low insertion loss.

The proposed filter design is optimized for specific frequency bands such as LTE or 5G sub-6 GHz, demonstrating excellent frequency selectivity, thermal stability, and scalability. Simulation results using FEM and circuit-level modeling validate the filter's performance, with key parameters including center frequency, bandwidth, insertion loss, and return loss meeting industry standards. This study underscores the potential of SMR-based filters in next-generation RF front-end modules, combining performance with CMOS compatibility and high-volume manufacturability.

List of Figures

Figure 2.1 Block diagram of MEMS resonator 6
Figure 2.2 Clamped-Clamped beam 7
Figure 2.3 Mass damper model of vibrating structure 8
Figure 3.1 General electric model for MEMS resonator 13
Figure 3.2 The mechanical and electrical analogy 14

Figure 4.1 Electric charge displacement and poling in a BAW resonator 18
Figure 4.2 Surface and Bulk micromachined 19
Figure 4.3 Wave propagation through SMRs and Bragg reflector 20
Figure 4.4 Topologies: ladder, lattice and mixed 22
Figure 4.5 Transmission coefficients of a ladder structure 23
Figure 4.6 FBAR-type BAW resonator 24
Figure 5.1 A typical graph of quality factor 27
Figure 5.2 SMR-type BAW resonator 28
Figure 5.3 Frequency spectrum of acoustic resonator 31
Figure 5.4 Lumped equivalent circuit of acoustic resonator 31
Figure 5.5 S-Parameter Vs frequency 33
Figure 5.6 Ladder and Lattice filter design 34
Figure 6.1 3D model of SMR 35
Figure 6.2 Electric potential and Electric field 36
Figure 6.3 Admittance and Quality factor Vs frequency 38
Figure 6.4 Quality factor Vs frequency 41
Figure 6.5 Admittance and Scattering parameter Vs frequency 42
Figure 6.6 Electrical circuit of SMR 43
Figure 6.7 S-parameter Vs frequency 43
Figure 6.8 Admittance Vs frequency 44

List of tables

Table 2.1. Types of MEMS and their applications 12
Table 3.1 Comparision between MEMS and Quartz Resonators 15
Table 3.2 Piezoelectric materials 17
Table 4.1 Comparision between FBAR and SMR Resonators
Table 6.1 Dimensions and materials for SMR resonator

Keywords: Multifrequency Microelectromechanical sytem resonator, Quality factor, Resonant frequency, Motional resistance

MEMS	Micro Electro Mechanical Systems
NEMS	Nano Electro Mechanical Systems
QF	Quality factor
ZnO	Zinc Oxide
AlN	Aluminium Nitride
PZT	Lead Zirconate Titanate
SAW	Surface Acoustic Wave
BAW	Bulk Acoustic Wave
FBAR	Film Bulk Acoustic Resonator
SMR	Solidly Mounted Resonator
FEM	Finite Element Method

Abstract ..... **i**

List of Figures ..... **ii**

List of Tables ..... **iii**

Abbreviations ..... **iv**

Chapter 1: Introduction

1.1 Background 2
1.2 Motivation 3
1.3 Thesis Organisation 5

Chapter 2: Literature Review

2.1 Resonance 6
2.2 MEMS Resonator 6

Chapter 3: Fundamentals of MEMS Resonator

3.1 MEMS resonator 13
3.2 Types of MEMS resonator 15
3.2.1 SAW Resonator 15
3.2.2 BAW Resonator 15

Chapter 4: SMR Structure and Operation

4.1 Bulk Acoustic Wave (BAW) Resonator 18
4.1.1 FBAR (Film Bulk Acoustic Resonator) 19
4.1.2 SMR (Solidly Mounted Resonator) 20
4.2 FBAR and SMR applications 21
4.3 Filter realization using BAW (FBAR or SMR) 22
4.4 BAW resonators 23

4.4.1 FBAR- type BAW resonators..... 23

Chapter 5: SMR-based Filter Design

5.1 Objectives.....26
5.2 SMR-type BAW resonator..... 28
5.3 Filter design.....30

Chapter 6: Simulation and Analysis

6.1 Device Simulation in COMSOL 35
6.2 Circuit Simulation in Cadence virtuoso 43

Chapter 7: Conclusion and Future Scope

7.1 Conclusion.....47
7.2 Future Scope.....48

References 49

1

INTRODUCTION

1.1 Background

With the rapid expansion of wireless communication systems, there is an increasing demand for compact, high-performance RF filters capable of operating at high frequencies with minimal power loss and signal distortion. Acoustic wave resonators, particularly Bulk Acoustic Wave (BAW) devices, have become integral in fulfilling these requirements. Among BAW technologies, Solidly Mounted Resonators (SMRs) stand out due to their structural robustness, high quality factor (Q), and compatibility with CMOS fabrication processes.

An SMR is a type of BAW resonator that confines acoustic energy vertically within a piezoelectric layer, typically Aluminum Nitride (AlN) or Zinc Oxide (ZnO), placed between two metal electrodes. Unlike traditional BAW devices that may require suspension in air (as in Film Bulk Acoustic Resonators - FBARs), SMRs are solidly attached to the substrate. To prevent energy leakage into the substrate, a Bragg acoustic reflector—composed of alternating layers of materials with differing acoustic impedances—is placed beneath the resonator. This reflector reflects acoustic waves back into the piezoelectric layer, enhancing energy confinement and minimizing losses.

In filter design, SMRs are used to create bandpass filters by arranging resonators ladder and shunt configurations. Their high electromechanical coupling coefficient (k^2) enables operation in GHz frequency ranges with sharp passband characteristics and excellent out-of-band rejection. Furthermore, SMRs offer better thermal stability and mechanical integrity compared to suspended structures, making them ideal for integration into high-density RF front-end modules, particularly in LTE, Wi-Fi, and emerging 5G systems.

1.2 Motivation

The motivation for designing filters with Solidly Mounted Resonators (SMRs) stems from their advantageous characteristics, particularly in the context of modern wireless communication systems and other high-frequency applications. Here are the key reasons why SMRs are a preferred choice for filter design:

1. High-Frequency Operation (above 1 GHz):

Superior performance at high frequencies: Unlike Surface Acoustic Wave (SAW) filters, which have limitations at higher frequencies, SMRs, a type of Bulk Acoustic Wave (BAW) filter, offer superior performance above 1 GHz. This is crucial for applications like 5G, Wi-Fi, and other advanced wireless standards that operate in the GHz range.

Miniaturization: As operating frequencies increase, the wavelength of the acoustic wave decreases, allowing for smaller resonant structures and, consequently, more compact filters. This is vital for the ever-decreasing size requirements of modern portable devices.

2. Excellent Performance Characteristics:

High Quality Factor (Q-factor): SMRs can achieve high Q-factors, which directly translates to low insertion loss in filters. Low insertion loss means less signal attenuation, leading to better signal integrity and power efficiency.

Good Power Handling Capability: SMRs exhibit robust power handling capabilities compared to some other resonator technologies. This is important in transmitter front-ends where signals can have significant power levels.

High Electromechanical Coupling Coefficient (k_{eff}): A high k_{eff} indicates efficient conversion between electrical and acoustic energy, enabling wider filter bandwidths. This is critical for applications requiring broad frequency bands.

Temperature Stability: Compared to some SAW devices, SMRs can offer improved temperature stability, which is essential for consistent filter performance across varying environmental conditions. This is often achieved by carefully selecting and designing the materials in the resonator stack.

3. **Integration with CMOS Technology:**

Compatibility with silicon wafer processing: SMRs are typically fabricated on silicon substrates and are compatible with standard CMOS (Complementary Metal-Oxide-Semiconductor) manufacturing processes. This allows for monolithic integration with other integrated circuits, reducing overall system size, cost, and complexity.

High-volume manufacturing: The compatibility with established semiconductor fabrication methods enables high-volume and cost-effective production of SMR-based filters.

4. **Robustness and Reliability:**

Structural Stability: SMRs are inherently more robust and less prone to mechanical damage during fabrication (e.g., dicing) compared to free-standing resonator structures (like some FBARs). This is because the acoustic energy is confined by a solid Bragg reflector rather than an air cavity.

Low Layer Tensions: The design of SMRs can lead to lower internal stresses within the layers, contributing to better long-term reliability.

5. **Energy Confinement and Spurious Mode Suppression:**

Acoustic Bragg Reflector: The core of an SMR is an acoustic Bragg reflector (or mirror), which consists of alternating layers of high and low acoustic impedance materials. This multi-layered structure efficiently reflects the acoustic energy back into the piezoelectric resonator, preventing energy leakage into the substrate and maintaining a high Q-factor.

Spurious Mode Suppression: While challenging, the design of the Bragg mirror and electrode shapes can be optimized to suppress unwanted shear waves and other spurious modes, which can degrade filter performance by introducing undesirable resonance peaks.

In summary, the drive to design filters with Solidly Mounted Resonators is motivated by the need for high-performance, compact, and cost-effective filtering solutions in the ever-evolving landscape of high-frequency wireless communications and other advanced electronic systems. Their ability to deliver high Q-factors, good power handling, and CMOS compatibility at GHz frequencies makes them a leading technology for these applications.

1.3 Thesis Organisation

The seven chapters that make up this research study thesis are covered below.

Chapter1:

Explains the project's introduction, background data, reasons for initiating the project, and thesis structure.

Chapter2:

This chapter discuss about resonator, MEMS resonator, and mass-damper model and electrical equivalent model.

Chapter3:

This chapter discuss about working principle of MEMS resonator, advantages of MEMS resonators, types of MEMS resonator (SAW and BAW), resonator modes and piezoelectric materials.

Chapter4:

This chapter explains about SMR structure and operation, BAW resonators (FBAR and SMR) and their applications and also filter realization using BAW resonators.

Chapter5:

This chapter discuss about SMR-based filter design, Quality factor, Resonance frequency, Motional resistance, Electromechanical coupling coefficient, filter design and characterization of resonators.

Chapter6:

This chapter discuss about Simulation and Analysis: Device Simulation in COMSOL and Circuit Simulation in Cadence virtuoso(Layout and Fabrication)

Chapter7:

This chapter presents the conclusion and future work.

2

LITERATURE REVIEW

2.1 Resonance

Resonance is basically a phenomena in which the system responds selectively to certain frequencies. When a system has the ability to store and transfer energy from one mode to another, it is said to be in resonance. Resonance can occur in a variety of domains, including mechanical, electrical, electromagnetic, optical, and acoustic, depending on the method of action. In the electrical world, a resonator is a circuit made up of an inductor, resistor, and capacitor linked in series or parallel. Energy is stored in the electrical field when the capacitor is charged and in the magnetic field when current passes through the inductor. The system oscillates when energy is constantly transferred between the two. The inductor and capacitor impedances cancel each other out when resonance occurs because they are equivalent but opposite. The frequency at which this phenomenon occurs is referred to as the resonant frequency. At resonance, the circuit will have the lowest impedance.

2.2 MEMS Resonator

The concept of a micromechanical resonator is easily understood by using the simple macroscale example of a guitar string of a given length made of a nickel and steel alloy that vibrates at a specified resonance frequency when plucked.

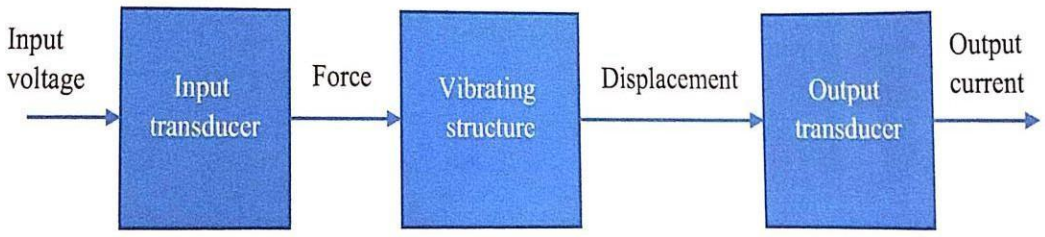


Figure 2.1 Block diagram of MEMS resonator

1. Using an input-transducer, an electrical signal is transformed into a mechanical signal, or electrostatic force (also known as piezoelectric, magnetostatic, etc.).
2. A mechanical resonant structure that generates electrostatic force and is capable of vibrating in one or more modes.

3. An output-transducer that senses the motion of the vibrating structure, hence converting the mechanical signal back to an output electrical signal.

Every mechanical structure, including beams and disks, will vibrate at one of several natural resonance modes. This is comparable to how wine glasses vibrate when struck firmly, producing a noticeable auditory frequency. These happen at very low frequencies at such macroscales, usually below a few kilohertz. Much higher resonance frequencies (such as several MHz or even up to GHz) can be achieved by reducing the dimensions into the microscale.

Applying stresses to mechanical structures at particular frequencies—referred to as the resonant frequencies—forces them into resonance.

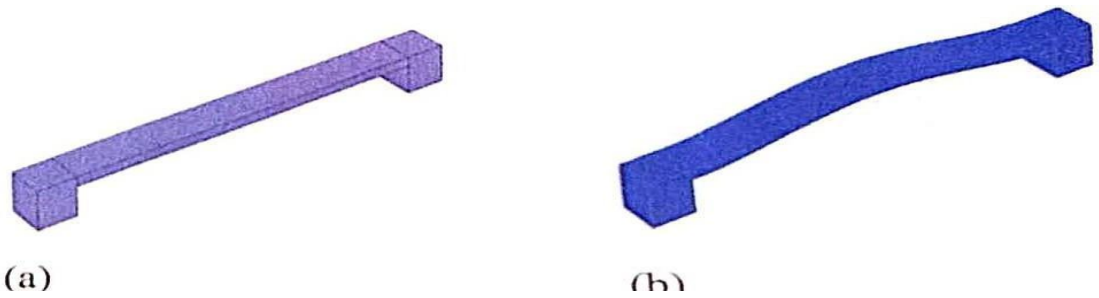


Figure 2.2 Clamped-clamped beam (b) The deformed beam at its natural eigenfrequency represented in three dimensions

Due to their small size, these beams have relatively high resonance frequencies. The resonance frequency for smaller beams can be as high as around 100 MHz. Transducers are required to supply the mechanical forces required to bring the resonator into resonance. The main methods of operation for these transducers are thermal, magnetic, piezoelectric, or electrostatic. When compared to other transducer types, piezoelectric transducers are more effective in operating at resonance.

Mass damper model and electrical equivalent model

A damped, driven harmonic oscillator is used to represent the behavior of a micromechanical resonator. The micromechanical structure is the same as that of a basic mass-spring system, in which the stiffness of the material provides the force that pulls the suspended mass back toward the equilibrium position. In extensional mode resonators, the spring constant is determined by the elongation resistance (Young's modulus) in the resonator mass, whereas the bending resistance of a membrane serves as the spring in flexural resonators.

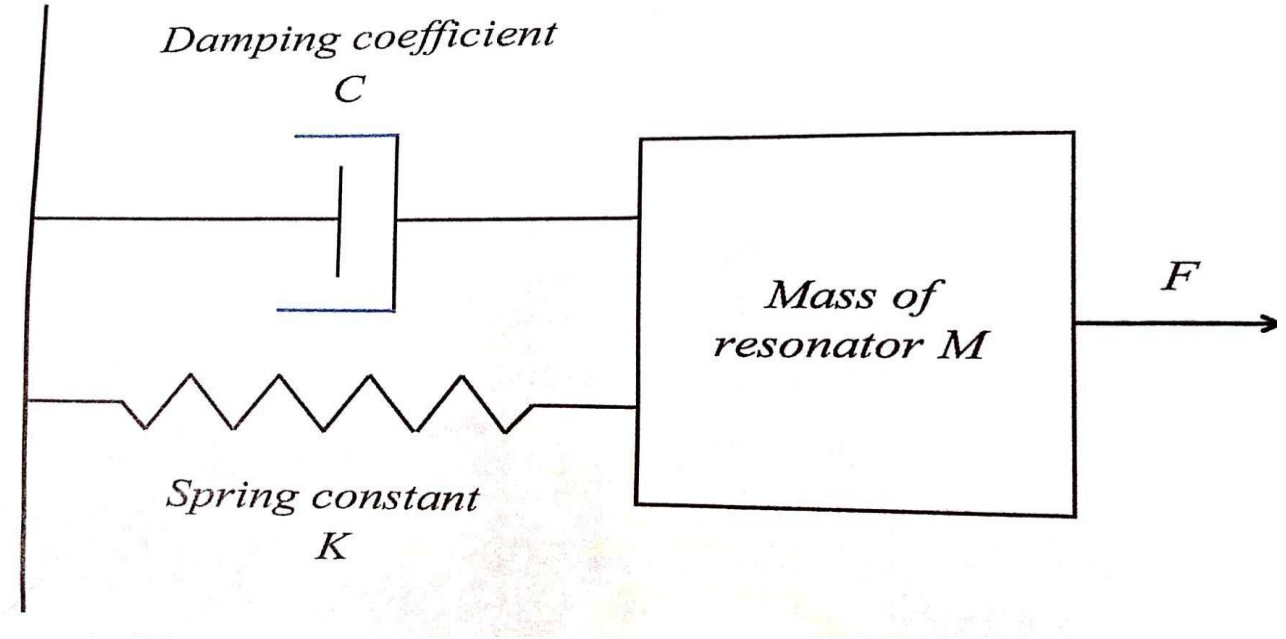


Figure 2.3 Model of a vibrating structure with mass dampers

The mass-spring mechanical system is governed by a linear differential equation that balances forces in keeping with Newton's Law. The forces operating on the mass are the external driving force, F(t), the damping force proportional to speed, and the restoring force proportional to displacement.

$$m\left(\frac{d^2x}{dt^2}\right) + c\frac{dx}{dt} + kx = F(t) \qquad (2.1)$$

The inductor, capacitor, and resistor (LCR) tank circuit is an example of a system that follows a comparable differential equation.

$$L\left(\frac{d^2q}{dt^2}\right) + R\frac{dq}{dt} + \frac{q}{C} = V(t) \qquad (2.2)$$

where the charge (q) is the electrical equivalent of the mechanical displacement around the equilibrium position (x), the capacitance (C) is inversely related to the mass-spring system spring constant (k), the resistance (R) is the damping or loss coefficient (c), and the inductance (L) is related to the mass (m).

A literature review on filter design using Solidly Mounted Resonators (SMRs) reveals a significant body of research driven by the demand for high-frequency, high-performance, and miniaturized

filters in modern communication systems. SMRs, a type of Bulk Acoustic Wave (BAW) resonator, offer distinct advantages over alternative technologies like Surface Acoustic Wave (SAW) devices, particularly above 1 GHz.

1. **Fundamental Principles and Structure:**
   The foundational concept of SMRs, as first proposed by Newell in 1965, involves a piezoelectric thin film (e.g., AlN, ZnO, AlScN) sandwiched between two electrodes, deposited on an acoustic Bragg reflector (ABR). This ABR, comprising alternating layers of high and low acoustic impedance materials (e.g., Mo/SiO2, W/SiO2, HfO2/SiO2), prevents acoustic energy from leaking into the substrate, thereby achieving acoustic isolation and a high Quality factor (Q) for the resonator. The thickness of each layer in the Bragg mirror is typically a quarter-wavelength of the acoustic wave at the operating frequency, optimized for maximum reflection.
2. **Key Performance Metrics and Materials:**
3. **Electromechanical Coupling Coefficient (k_{eff}^2):** A crucial parameter determining the achievable bandwidth of the filter. Researchers continuously explore new piezoelectric materials with higher k_{eff}^2. compared to traditional AlN, enabling wider bandwidths for applications like 5G.
4. Achieving high Q-factors in SMRs is a constant research focus, often involving optimization of the Bragg reflector layers, electrode materials, and fabrication processes to minimize acoustic losses.

   Temperature Stability: SMRs generally exhibit better temperature stability than SAW devices. Further improvements involve material engineering (e.g., using materials with negative temperature coefficients to compensate for positive ones) or active compensation techniques like ovenization, as explored in some biosensing applications to ensure accuracy despite temperature variations.

   Power Handling: SMRs are well-suited for high-power applications, making them attractive for transmitter front-ends. Research in this area focuses on optimizing electrode design and material choices to withstand higher power levels without degradation.

3. **Filter Topologies and Design Methodologies:**
4.

Ladder-Type Filters: The most common topology for SMR filters, consisting of series and parallel resonators. The design involves careful optimization of resonator frequencies, areas, and inter-resonator coupling to achieve desired passband characteristics (low insertion loss, steep

skirts) and out-of-band rejection. Analytical models like the Mason model are widely used for initial design, followed by advanced finite element analysis (FEA) simulations (e.g., in COMSOL Multiphysics) for detailed optimization and parasitic effects analysis.

Lattice and Stacked Architectures: While ladder-type is prevalent, other topologies are explored to achieve specific filter characteristics, such as improved rejection or smaller footprints.

5. Wideband Filter Design: Achieving wide bandwidths is a significant challenge. Strategies include utilizing piezoelectric materials with high k_{eff}^2 (like AlScN or single-crystalline LiNbO3 thin films), optimizing the acoustic impedance mismatch in the Bragg reflector, and exploring novel resonator designs.

4. **Fabrication Techniques:**

   Thin-Film Deposition: Radio-frequency (RF) magnetron sputtering is a primary technique for depositing piezoelectric films (AlN, AlScN) and Bragg reflector layers (e.g., Mo, SiO2, HfO2, W).

   Photolithography and Etching: Standard semiconductor fabrication techniques are employed for patterning electrodes and defining resonator geometries.

   Wafer Bonding and Transfer: For advanced SMR structures, particularly those involving heterogeneous integration (e.g., single-crystalline piezoelectric films on silicon substrates), wafer bonding and layer transfer techniques are becoming increasingly important to achieve superior material properties and device performance.

5. **Design Challenges and Current ResearchTrends:**

   Spurious Mode Suppression: A persistent challenge in SMR filter design is the suppression of unwanted spurious modes (e.g., shear modes, lateral modes) that can degrade filter performance. Research explores techniques like electrode apodization (shaping electrodes to confine acoustic energy), careful Bragg mirror design to preferentially reflect longitudinal waves,and the use of acoustic absorbing layers.

   Miniaturization: As devices shrink, the demand for smaller filters intensifies. Research focuses on optimizing the footprint of individual resonators and the overall filter layout, as well as exploring novel cavity designs that can house multiple resonators in a smaller area. Integration with CMOS: Enhancing the compatibility and monolithic integration of SMRs with CMOS circuits is a key trend to enable highly integrated RF front-ends, reducing parasitic losses and system complexity.

   Novel Materials and Structures: Continuous exploration of new piezoelectric materials (e.g., doped AlN, ferroelectric materials) and Bragg reflector materials (e.g., tailored a-

SiOCN:H for lower acoustic impedance) for improved performance (higher k_{eff}^2, Q, and temperaturestability).

7.**Biosensing Applications:** Beyond RF filters, SMRs are gaining traction in biosensing due to their high sensitivity and robust structure. This area involves specific design considerations for functionalizing the resonator surface and optimizing its response to biological analytes. In conclusion, the literature on SMR filter design demonstrates a mature field with ongoing innovation. Driven by the demands of advanced wireless communication, research continues to push the boundaries of performance, miniaturization, and integration, exploring new materials, complex filter topologies, and sophisticated fabrication.

The first wireless transmission was demonstrated by Sir Guglielmo Marconi in 1895. Wireless networks have various applications, including satellite transmission, radio and television broadcasting, sensor networks, global positioning systems (GPS), global mobile communications systems, and—most importantly—modern smartphones. As the number of wireless communication devices increases daily, new methods to further reduce the size of RF front-ends while lowering their cost and power consumption are sought for.

In the best wireless transceivers and subsystems, resonators—and hence oscillators and filters—have been made using high-quality factor (Q) and low motional resistance (Rm). The development of tiny resonators that can be directly integrated into an integrated circuit (IC) has taken a great deal of time and effort from several researchers.

MEMS is the term used to describe the integration of mechanical components, sensors, actuators, and electronics using microfabrication technology on a single silicon substrate. The micromechanical components are made using "micromachining" techniques such lithography, etching, and deposition. The mechanical and electromechanical devices are formed by adding new structural layers or selectively etching away silicon components.

Category	Application
Sensors of Inertia	Gyroscopes and airbag accelerometers
Sensors for pressure	IOP, microphone, blood pressure, and vehicle tire pressure
Microfluidics/ BioMEMS	Inkjet printer head, DNA chips, and microbioanalysis
Optical MEMS	Adaptive optics and Optical fiber switch
MEMS for power and energy	High power switches and an energy harvesting
RF MEMS	Switches, antenna, filter/oscillator, and high Q inductor

Table 2.1 Types of MEMS and their applications

.

3

FUNDAMENTALS OF MEMS RESONATOR

3.1 MEMS resonator

A MEMS resonator consists of transformers for energy transmission between electrical and mechanical disciplines and a reverberative mechanical structure. Reverberative mechanical structures have been seen thus far since shafts, disks, or plates may all be modeled as spring-mass-mute systems.

A MEMS resonator (Micro-Electro-Mechanical Systems resonator) is a miniaturized device that uses mechanical vibrations to perform functions such as signal filtering, frequency reference, and sensing. It operates by converting electrical energy into mechanical motion and then back to electrical energy using integrated transducers.

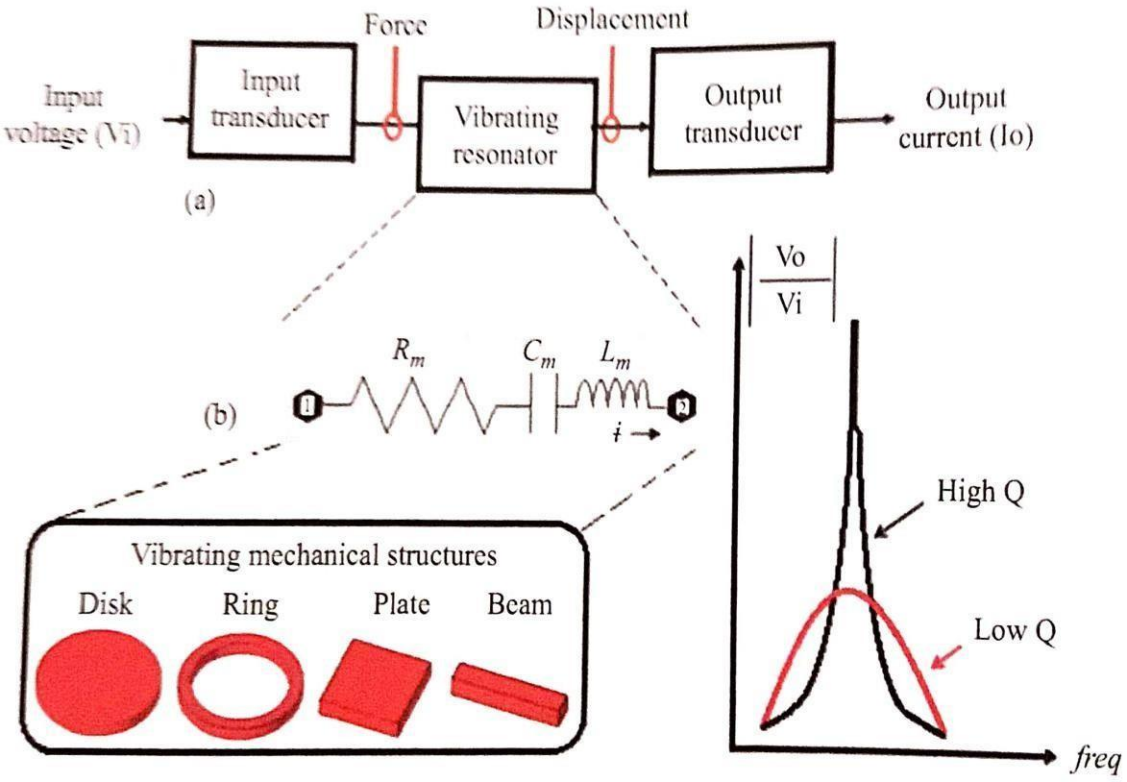


Figure 3.1 (a) A MEMS resonator block diagram and (b) a generic electric model

Working Principle

. Input transducer converts electrical input (voltage) into mechanical force.

. This force excites a vibrating mechanical structure—such as a disk, ring, beam, or plate.

. The mechanical vibration (displacement or deformation) is converted back to electrical output using an output transducer.

.This electromechanical energy conversion is modeled using a spring-mass-damper system and represented electrically by a series RLC circuit.

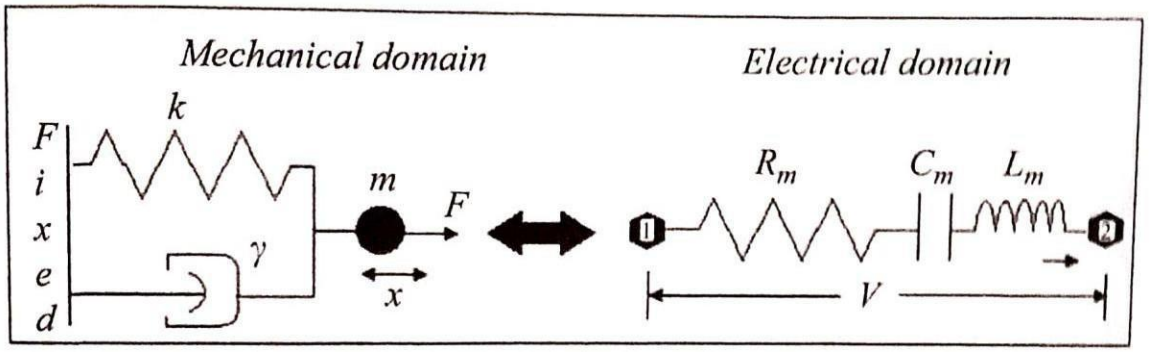


Figure 3.2 The mechanical and electrical analogy

Advantages of MEMS Resonators

Miniaturization: MEMS devices are extremely small (e.g., ~400 µm), allowing integration in compact systems.

CMOS compatibility: Easily integrated with standard semiconductor processes.

Low cost: Cheaper to manufacture in large volumes compared to quartz crystals.

High Q-factor: Offers reasonably high quality factor (75,000–150,000), which determines frequency selectivity and stability.

Robustness: Good immunity to shock and vibration, making them ideal for mobile and aerospace applications.

Comparison with Quartz Resonators

Feature	Quartz Resonator	MEMS Resonator
Dimensions	2-5 mm	~400 um
Range of frequencies	1-80 MHz	1-50 MHz
Q-factor	100,000-200,000	75,000-150,000
Compatibility with CMOS	No	Yes
Vibration/Shock Immunity	Poor	Good
Cost	High	Low

Table 3.1 Comparision between MEMS and Quartz Resonators

3.2 Types of MEMS resonator:

Miniaturization and reduced power consumption have drawn a lot of attention from the sensor, telecommunications, and mobile radio device industries. Acoustic micro resonators are manufactured to meet the demands of the sensor and mobile radio equipment industries for smaller and lower-power devices. The way acoustic devices operate is by allowing acoustic waves to pass through them, which causes them to vibrate at a frequency that is compatible with their size. The two fundamental forms of acoustic propagation are surface acoustic wave (SAW) and bulk acoustic wave (BAW) resonators.

3.2.1 SAW Resonator

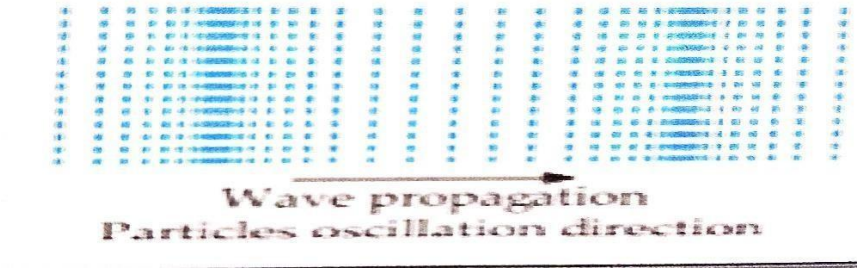
A surface acoustic wave (SAW) occurs when an acoustic wave is confined and that will travel along the interface between both the substrate and the air, similar to the ripples seen on a water surface when hit by stone. This type of acoustic wave's amplitude decreases exponentially with depth into the substrate, and it can only propagate closer to the surface of a semi-infinite solid. SAW uses frequencies ranging from 30 MHz to certain GHz.

3.2.2 BAW Resonator

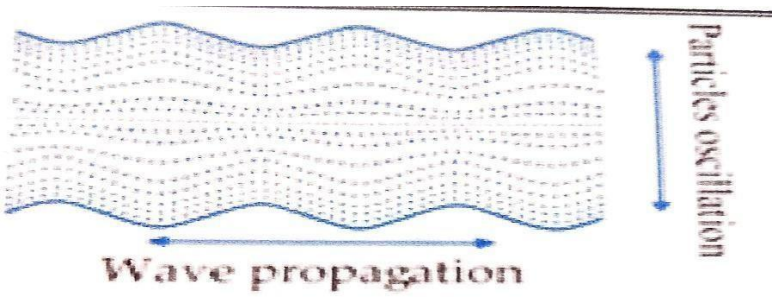
A bulk acoustic wave (BAW) is a wave that travels through the bulk of the material's medium and it exist in the majority of its volume of the medium, similar to a sound wave that traverses through the air. BAWs are flexible waves that travel in a solid medium and can be divided into three categories: longitudinal waves, transverse (shear) waves, and lamb waves. The characteristics along with its schematic is described in the figure below.

Types of waves

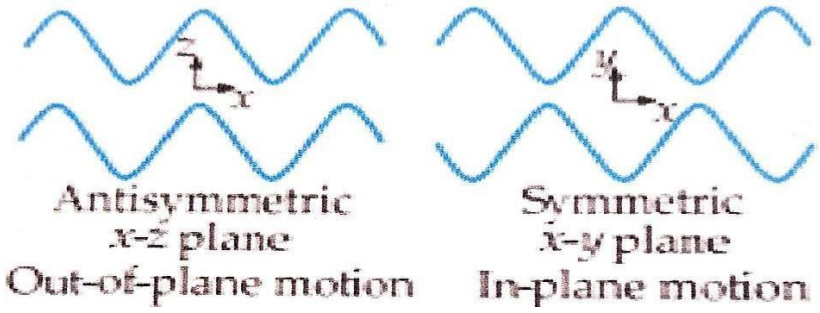
Longitudinal wave: propagation across the medium in the direction of the oscillation or vibration of the particles, or in the opposite direction. Another name for it is pressure waves.



Transverse wave: propagation across the medium perpendicular to the direction of particle oscillation. Shear-mode waves are another name for it.



Lamb wave: It is found in thin plates, also known as plate waves, and the motion of the particles occurs in the plane perpendicular to the plate and the wave's direction of propagation. It is separated into two categories: symmetric and anti-symmetric waves.



The actuation and detection processes in BAW device operation are the same as they are in SAW resonators: i.e., piezoelectric and inverse piezoelectric effects. BAW's operational frequency is in the GHz range. There are two types of BAW (Bulk Acoustic Wave) resonator: Solidly Mounted Resonator (SMR) and Thin-film Bulk Acoustic Wave Resonator (FBAR).

Materials for piezoelectric resonators

Material	Type	Properties	Applications
Quartz(SiO_2)	Natural crystal	Stable, low loss, low temperature coefficient, low coupling	Precision timing (e.g., watches, clocks, oscillators)
Aluminium Nitride (AlN)	Ceramic	CMOS compatible, high thermal conductivity, moderate piezoelectricity	RF MEMS, FBARs, high-frequency resonators
Zinc Oxide (ZnO)	Ceramic	Strong piezoelectric effect, transparent, easy to deposit	SAW/BAW devices, thin-film sensors, actuators
Lead Zirconate Titanate (PZT)	Ceramic (ferroelectric)	Very high piezoelectric coefficients, not CMOS compatible, contains lead	Actuators, sensors, medical ultrasound, high-displacement devices
Lithium Niobate ($LiNbO_3$)	Single crystal	High electromechanical coupling, birefringent, difficult to integrate with CMOS	SAW devices, modulators, filters
Lithium Tantalate ($LiTaO_3$)	Single crystal	Similar to $LiNbO_3$ but with better temperature stability	SAW resonators, oscillators
Gallium Orthophosphate ($GaPO_4$)	Single crystal	High thermal stability, similar to quartz	Harsh environment sensors
Gallium Nitride (GaN)	Semiconductor	High breakdown voltage, used in combination with AlN	High-power and high-frequency devices

Table 3.2 Piezoelectric materials

4

SMR STRUCTURE AND OPERATION

4.1 Bulk Acoustic Wave (BAW) Resonators

Bulk Acoustic Wave (BAW) resonators function by allowing acoustic waves to propagate through the entire thickness of a piezoelectric material layer. This distinguishes them from Surface Acoustic Wave (SAW) devices, where wave movement is limited to the surface region. In BAW resonators, the acoustic waves—either longitudinal or shear-transverse—cause deformation throughout the bulk of the material. These devices typically use thin-film piezoelectric materials to achieve this effect.

The operation of BAW resonators relies on both the direct and inverse piezoelectric effects: applying an electrical signal induces mechanical strain in the material, while mechanical deformation generates an electrical response. This two-way conversion enables both actuation and signal detection in BAW-based systems.

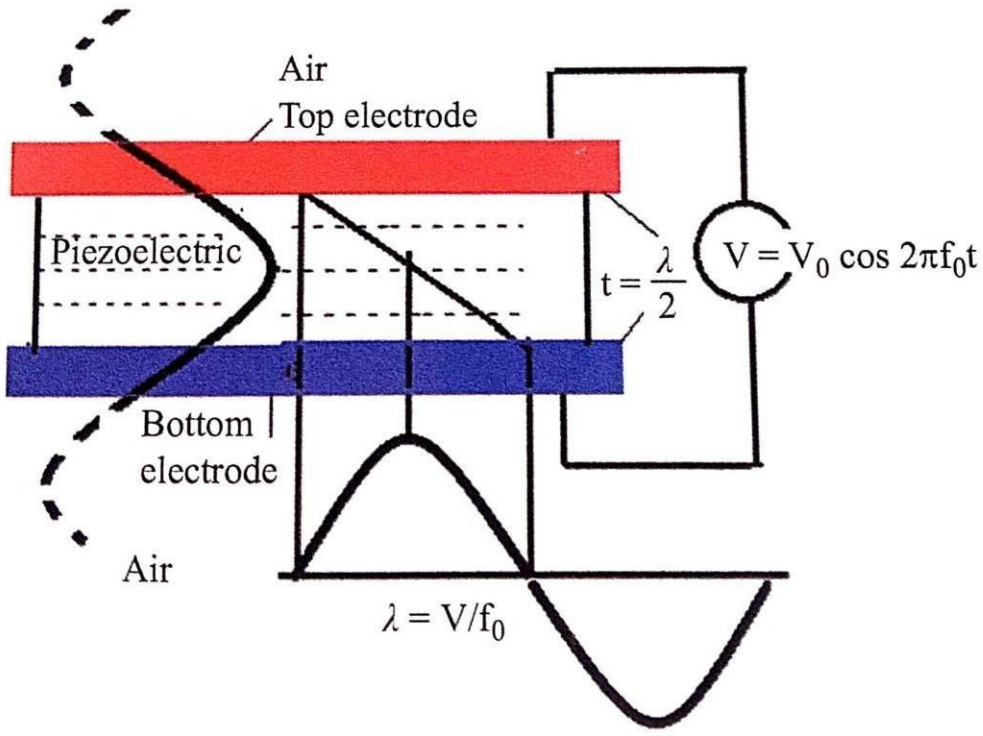
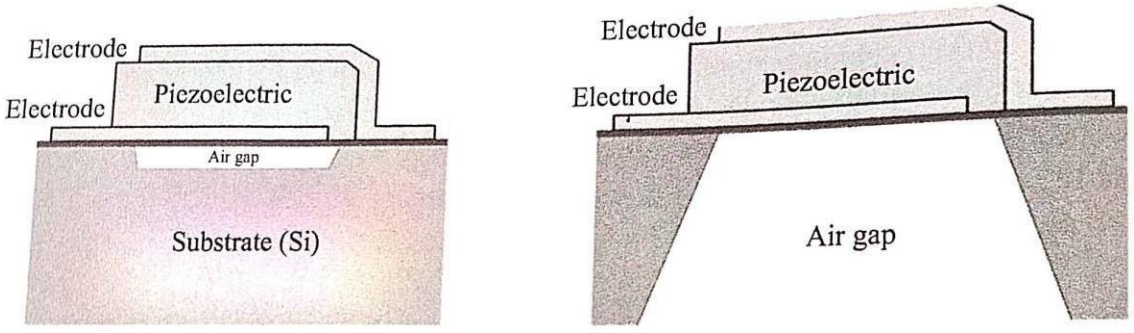


Figure 4.1 Electric charge displacement and poling in a BAW resonator due to an electric Potential apllied to its electrodes

There are two main types of BAW (Bulk Acoustic Wave) resonators, based on how the acoustic waves are confined and how the structure is built:

4.1.1 FBAR (Film Bulk Acoustic Resonator)

An FBAR consists of a piezoelectric layer positioned between two electrodes, designed to be acoustically isolated from its surroundings. Common piezoelectric materials used in these devices include aluminum nitride (AlN) and zinc oxide (ZnO). To achieve this isolation, micromachining processes are applied to separate the resonator from the underlying substrate. This enhances the quality factor by minimizing acoustic energy loss. The device structure typically includes an air cavity, gap, or thin membrane beneath it, created through surface or bulk micromachining techniques from either the front or back side.



(a) **(b)**

Figure 4.2 (a) Surface micromachined and (b) bulk micromachined

Also known as Thin Film BAW Resonator, FBARs use a thin piezoelectric layer sandwiched between two electrodes. The key feature is that the acoustic wave is confined within the thin film. **Operating Principle:** A standing acoustic wave is formed across the film thickness.

Key Characteristics:

High-frequency operation (up to several GHz)
Small size, suitable for integration in RF modules
Fabricated on a solid substrate or membrane
Applications: RF filters in smartphones, wireless communication systems.

4.1.2 SMR (Solidly Mounted Resonator)

SMRs operate on principles similar to FBARs but differ in their isolation method. Instead of using an air gap, SMRs incorporate a multilayer Bragg reflector, composed of alternating layers of materials with different acoustic impedances and a thickness of one-quarter wavelength (λ/4). These layers reflect acoustic waves back into the resonator, effectively isolating it from the substrate and preventing energy loss.

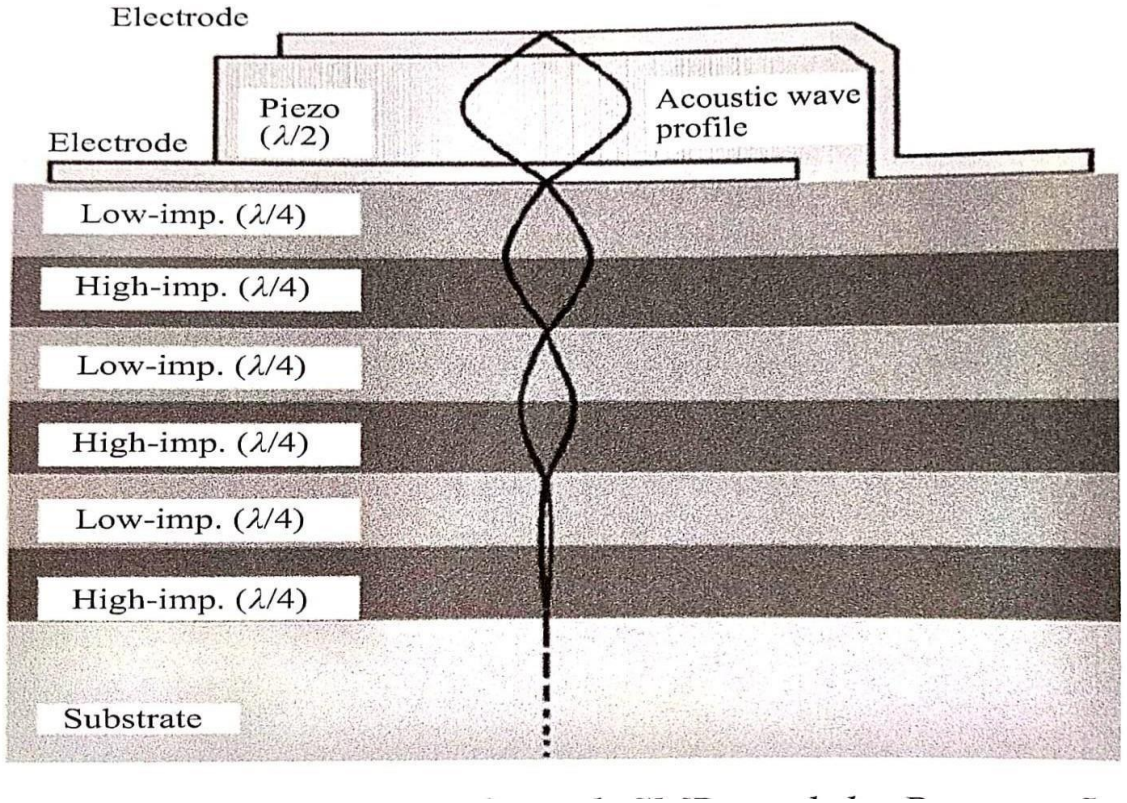


Figure 4.3 Wave propagation through SMRs and the Bragg reflector

The significant difference in acoustic impedance between the alternating λ/4-thick layers in SMRs results in the reflection of bulk acoustic waves back into the resonator, effectively trapping the energy within the device's acoustic layer. This multilayer structure functions as a reflective barrier, often referred to as a Bragg reflector. SMR devices are known for their structural durability, minimal mechanical stress, and low susceptibility to damage during manufacturing and assembly processes such as dicing. Conversely, FBARs typically offer superior quality (Q) factors and better thermal isolation because of their air-gap structure. Nevertheless, the Q factor in SMRs can be adjusted by varying the number of layers in the Bragg reflector to meet specific performance requirements.

An SMR is a type of BAW resonator where the piezoelectric layer is deposited on top of a Bragg reflector (an acoustic mirror made of alternating high and low acoustic impedance layers).

Operating Principle: The Bragg reflector prevents energy leakage into the substrate by reflecting acoustic waves back into the piezoelectric layer.

Key Characteristics:

Easier to integrate on standard semiconductor substrates
More robust mechanical support compared to FBARs
Applications: Mobile phones, wireless devices, RF filters

Type	Structure	Wave Confinement	Substrate Interaction	Common Use
FBAR	Thin film on membrane or substrate	Within piezo layer	Free-standing or partially suspended	RF filters
SMR	Piezo on Bragg reflector stack	Above acoustic mirror	Mounted on substrate	Integrated RF modules

Table 4.1 Comparision between FBAR and SMR Resonators

4.2 FBAR and SMR apllications

FBAR technology is utilized across a wide range of applications, from radio frequency (RF) systems to various sensing technologies. While the telecommunications sector initially drove the advancement of FBAR-based solutions, recent years have seen its adoption in numerous sensing scenarios. Early RF implementations of FBARs focused on creating entirely passive components—such as filters and duplexers—that could effectively compete with existing surface acoustic wave (SAW) and ceramic alternatives. In sensing applications, FBAR devices function as core components within systems that rely on piezoelectric principles for actuation or detection. These applications include mass sensing as well as the detection of chemical, liquid, or gaseous substances.

4.3 Filter realization using BAW (FBAR or SMR)

BAW resonators, either SMRs or FBARs, are set up in parallel to form a filter. Impedance transformation and mode transitions, such as from symmetric to differential modes, are not supported by this family of BAW filters. Lattice and ladder structures, often known as "Π" and "T" kinds, respectively, are the two most used filter configurations. Two separate kinds of resonators that resonate at different frequencies must be used in order to build these filters. By including an additional layer into the conventional resonator, this frequency difference may be accomplished. The transmission properties of a ladder-type filter are shown in Figure 4.5.

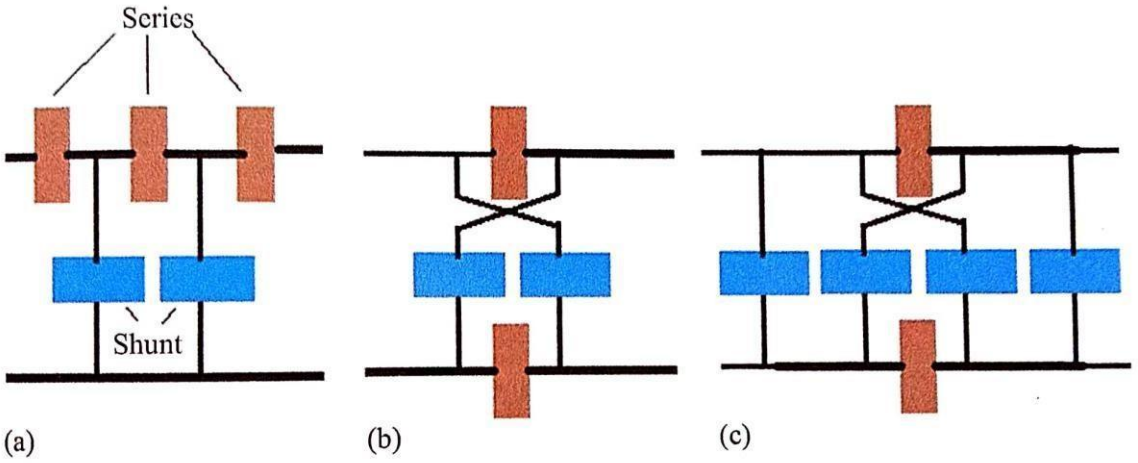


Figure 4.4 Topologies: (a) ladder, (b) lattice, and (c) mixed

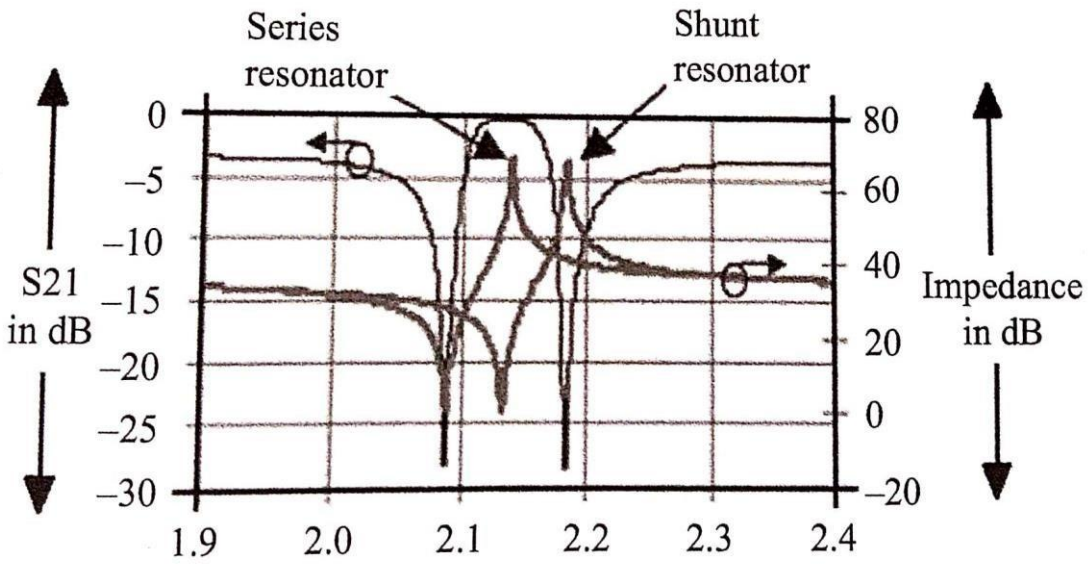


Figure 4.5 Transmission coefficients of a ladder structure with two resonators

4.4 BAW resonators

An acoustic insulating structure between the piezoelectric transducer and the substrate is necessary to prevent this kind of loss. It should be noted that in a piezoelectric transducer for signal processing applications, such an acoustic insulation construction is employed to limit the appropriate fundamental mode in addition to suppressing energy loss. It is preferable to have a high coupling coefficient and to adequately isolate the primary resonance from the harmonics and spurious response in order to use the BAW resonators for signal processing tasks like filtering.

In the 1980s, Nakamura et al., Lakin and Wang, and Grudkowski et al. reported using micromachined devices to limit the basic mode. these structures thinned the support substrate to improve the coupling coefficient and eliminate encroaching overtone harmonics. In the next part, we address BAW resonators by dividing them into two types of common acoustic isolation structures: solidly mounted resonators (SMRs) and thin-film bulk acoustic resonators (FBARs).

4.4.1 FBAR-type BAW resonators

A thin-film bulk acoustic resonator (FBAR) is a structure that has a free-standing piezoelectric resonator. The silicon substrate was anisotropically etched using an alkaline etchant in the early FBARs. However, from the viewpoint of efficient utilisation of the chip area, a structure fabricated by vertical plasma etching (Bosch process) was proposed as shown in Figure 8.18(a). This technology has been commercialised as a filter for use in 5-GHz-band wireless LANs.

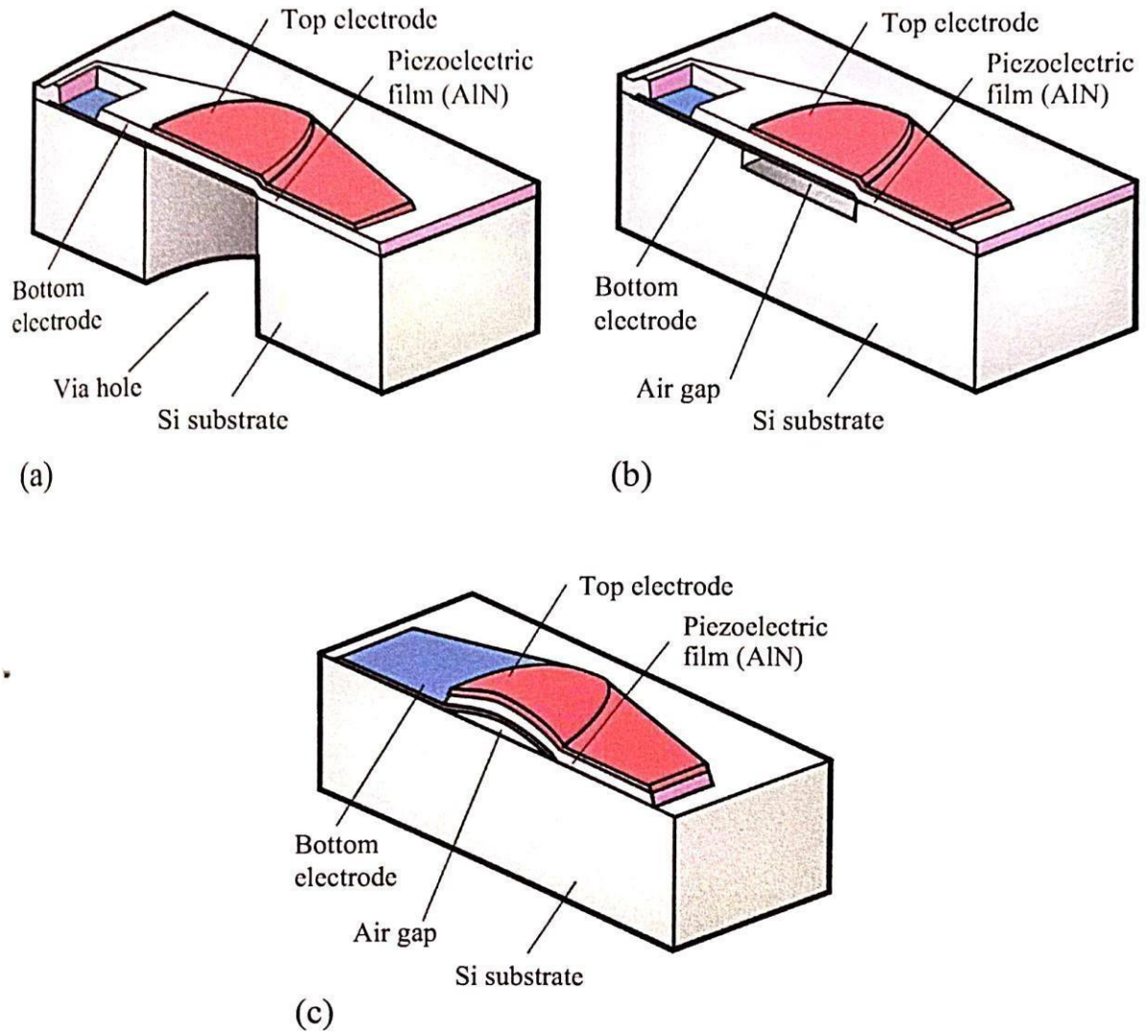


Figure 4.6 FBAR-type BAW resonator

A buried sacrificial layer, which is created by oxide deposition into the shallowly etched substrate (swimming-pool-like structure) and chemical mechanical polishing (CMP), is used in the most common FBAR structure, which is depicted in Figure. This structure was the first to be applied to a duplexer (US PCS). By utilizing the buried sacrificial layer, a wide air gap is created, which effectively prevents sticking and shortens the time needed for sacrificial layer etching.

The 1980s saw the first reports of active circuits and BAW devices being integrated. These BAW resonators' structure featured a tiny airgap created by etching a patterned sacrificial layer onto the substrate. However, without a specialized method, as seen in Figure 4.6(b), it was too challenging to achieve a high yield because the stress control of piezoelectric films had not yet been established. A piezoelectric film deposition method that allows for independent control of both stress and film quality has emerged in recent years.

As seen in Figure 4.6(c), an air-gap-type FBAR with a respectable yield has therefore been presented, in which the stress applied to the film to establish and sustain the air gap deforms the piezoelectric resonator into a dome shape.

5

SMR-based Filter Design

5.1 Objectives

(a) Resonance frequency (f_r)

The frequency at which the resonator oscillates with the largest amplitude is known as the resonance frequency. The resonance frequency, ωr, may be determined using the resonator's spring arrangement (k) and the mass of the resonating structure (m).

$$\omega r = \sqrt{\frac{k}{m}}$$

This idea underlies the operation of a piezoelectric resonator, which interconverts mechanical and electrical energy at a resonance frequency. The necessary resonance frequency is computed using a particular formula in order to establish the proper dimensions and guarantee the resonator operates as intended.

$$f_r = \frac{1}{2w_0}\sqrt{\frac{E_{eg}}{\rho_{eg}}}$$

(b) Quality factor (Q)

The ratio of the center frequency to the resonator's 3dB bandwidth may be used to estimate the quality factor Q.

$$Q = \frac{f_r}{3dB\ bandwidth}$$

Maximum conductance yields the series resonance frequency (f_s), while maximum resistance yields the parallel resonance frequency (f_p). A resonator's mechanical quality factor is defined as the ratio of energy stored (vibration stored in the resonator) to energy dissipated per vibration cycle.

$$Q = 2\pi \frac{Energy\ stored}{Energy\ dissipated\ per\ cycle\ of\ oscillation}$$

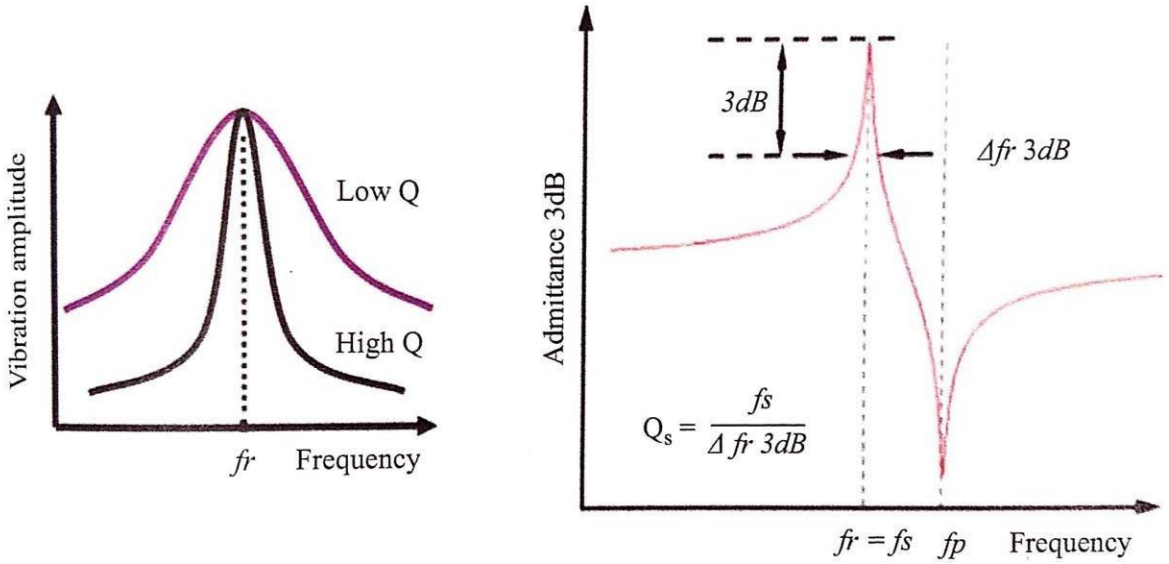


Figure 5.1 A typical graph of the quality factor

(c) Motional resistance (Rm)

When compared to electrostatically actuated resonators, piezoelectrically actuated resonators have lower motional resistance. Because it is closely related to the filter's insertion loss and the resonator's white noise, Rm is a crucial parameter.

(d) Electromechanical coupling coefficient (kt^2)

The electromechanical coupling coefficient (k_t^2) is the capacity of piezoelectric materials to convert electrical energy into mechanical energy and vice versa. As a result, its definition is the electrical energy to mechanical energy ratio. The mechanical and electrical energies that are stored are computed by

$$kt^2 = \frac{\pi^2}{4}\frac{f_p - f_s}{f_p} \approx \frac{\pi^2}{8}\frac{C_m}{C_0}$$

Piezoelectric materials with a greater piezoelectric coupling coefficient are preferred in order to enhance a resonator's effective coupling. Despite its modest dielectric constant, high breakdown voltage, and high electrical resistance, AlN has a marginally lower coupling coefficient than ZnO.

5.2 SMR-type BAW resonator

Bragg reflection films are frequently used to reflect electromagnetic waves, such as light. The construction shown in Figure was suggested as a BAW resonator, and the Bragg reflector mechanism can also be effective for acoustic waves.

In other words, layers with high and low acoustic impedances, each with a thickness of λ/4, are deposited alternatively to create the acoustic insulation between the resonator and the substrate. Because the free-standing film may be fabricated without the need for a challenging MEMS technique, this structure is known as a solidly mounted resonator (SMR).

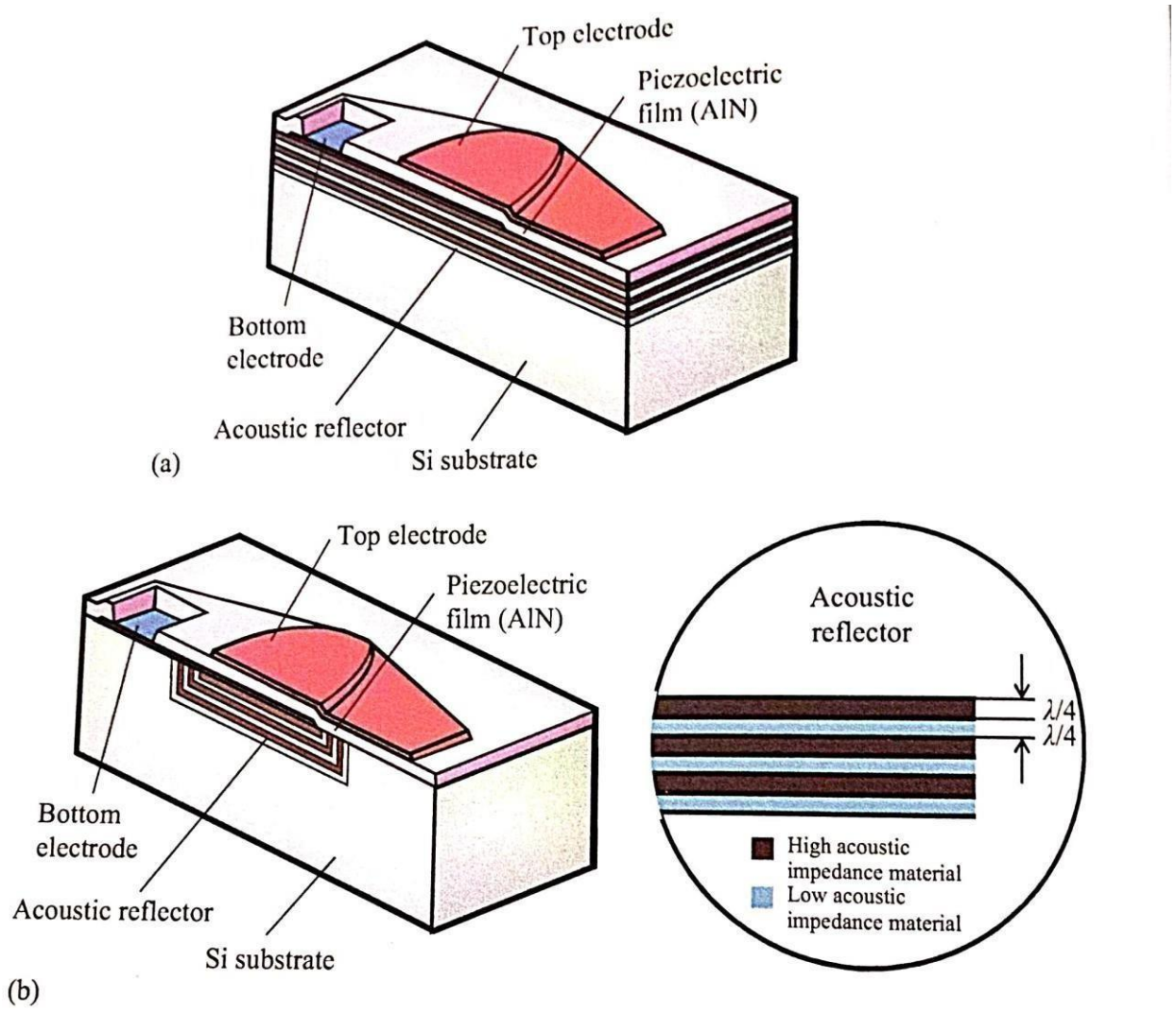


Figure 5.2 SMR-type Baw resonator

When employing the structure depicted in Figure, the resonators experience capacitive coupling with one another, which is problematic in applications like ladder filters where several resonators must be arranged with a high density. As a result, the structure depicted in Figure 5.2 is frequently utilized in practice. Bragg acoustic reflectors are constructed in a swimming pool-like structure that is made of silicon. Shallow etching and CMP are used to create the swimming pool-like structure, which is identical to that in Figure 5.2.

Three categories of vibrational energy leakage into the substrate are distinguished in Figure. Regardless of the kind of vibration, the air layer in the FBAR type insulates it. However, even if the principal resonance of the SMR type is solely based on longitudinal vibration in the thickness direction, the leakage of SV and SH waves cannot be disregarded. In order to create Bragg acoustic reflection films, layers having a thickness of $\lambda/4$ must be repeatedly deposited. They are optimized to reduce shear-type vibrations in addition to being specialized in suppressing longitudinal waves.

SMR-type BAW resonators have a lower Q-value than FBAR-type resonators because an air layer is better for acoustic isolation. But unlike the FBAR type, the SMR type offers a significant degree of design freedom through the use of a multilayer film.

5.3 Filter design

Characterisation of resonators

Figure 5.3 illustrates the double-resonance characteristic of SAW and BAW resonators, which consists of an anti-resonance produced by mutual interference between the electrostatic capacitance and mechanical vibration and a resonance of mechanical vibration. A Butterworth–Van Dyke (BVD) equivalent circuit is known to approach the double resonance shown in Figure 5.4. The loaded resonance Q (Qrl) and loaded anti-resonance Q (Qal) Q-values for such an equivalent circuit are defined as follows:

$$Q_{rl} = \frac{{}_r L_1}{R_S + R_1} = \frac{1}{(R_s + R_1)_r C_1}$$

$$Q_{al} = \frac{{}_a L_1}{R_1 + R_0} = \frac{1}{(R_1 + R_0)_a} \left(\frac{1}{C_1} + \frac{1}{C_0}\right)$$

$$\omega_r^2 = \frac{1}{L_1 C_1}$$

$$\omega_a^2 = \frac{1}{L_1}\left(\frac{1}{C_1} + \frac{1}{C_0}\right)$$

where the following angular resonance and anti-resonance frequencies are represented by ωr and ωa, respectively.

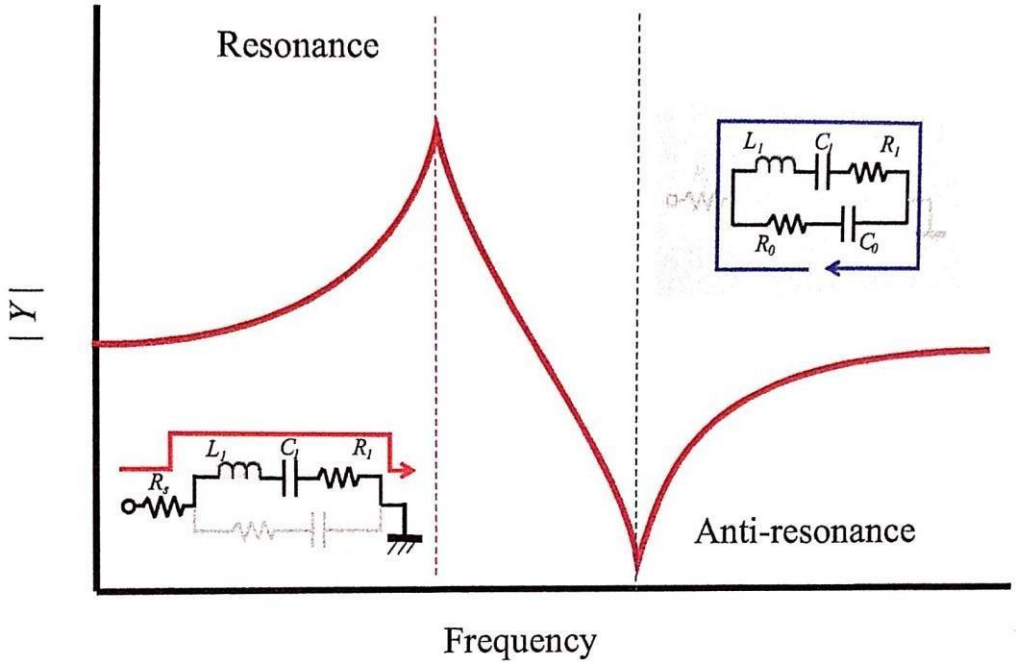
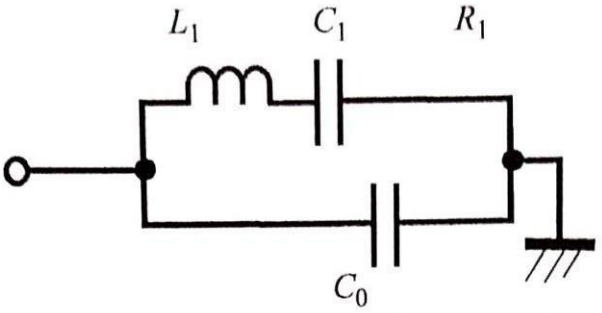
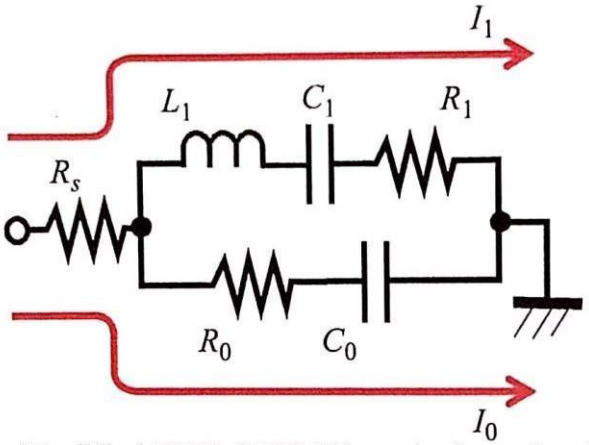


Figure 5.3 Frequency spectrum of acoustic resonator



(a) Butterworth–Van-Dyke (BVD) equivalent circuit



(b) Modified BVD (MBVD) equivalent circuit

Figure 5.4 Lumped equivalent circuit of acoustic resonator

A common metric for assessing the width of such a frequency band is the electromechanical coupling coefficient, or k_t^2. The passband width of filter applications is more closely associated with the effective electromechanical coupling coefficient k_{eff}^2, which is also utilized as an evaluation measure. The following is the definition of k_t^2 and k_{eff}^2

$$k_t^2 = \frac{\pi}{2}\frac{f_r}{f_a}\tan\frac{\pi}{2}\left(\frac{f_a - f_r}{f_a}\right)$$

$$\approx \frac{\pi^2}{4}\frac{f_r}{f_a}\frac{f_a - f_r}{f_a} = \frac{\pi^2}{8}\frac{C_1}{C_0}\frac{C_0 - C_1}{C_0}$$

$$k_{eff}^2 = \frac{f_a^2 - f_r^2}{f_a^2}$$

where the resonance and anti-resonance frequencies are denoted by f_r and f_a, respectively.
Here, we point out an issue with evaluating the double-resonance characteristic using the coupling coefficient mentioned before.

On the other hand, a higher coupling coefficient results in a lower Q-value. We refer to this as the Q-k trade-off. When the resonator's vibration is physically limited or a parasitic capacitance is coupled to it in parallel, the electromechanical coupling coefficient is suppressed. The decrease in coupling coefficient deterioration is unrelated to the resonator's enhancement of the Q-factor. The cosmetic improvement brought about by the Q-k trade-off must be taken into consideration in order to enhance the resonator's performance.

Additionally, a bothersome issue in resonator characterization is the Q- trade-off. One aspect of this trade-off is the rising frequency of loss cycles per unit of time. When talking about the Q- trade-off, there is a warning, even though this is not superficial. The input impedance decreases as the operation frequency rises, even for resonators with same dimensions. In this situation, the anticipated resonance and anti-resonance Q-values are more and lower than the actual loss, respectively.

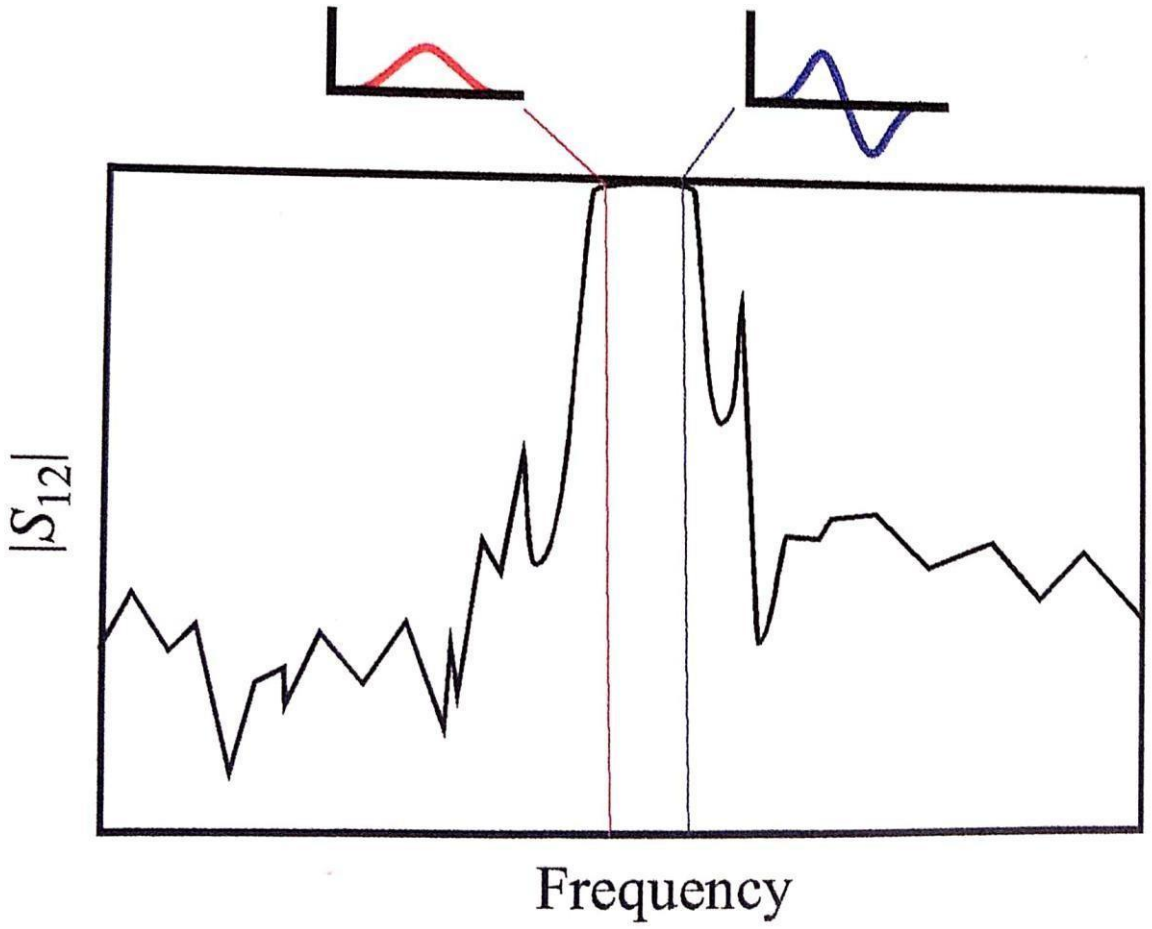
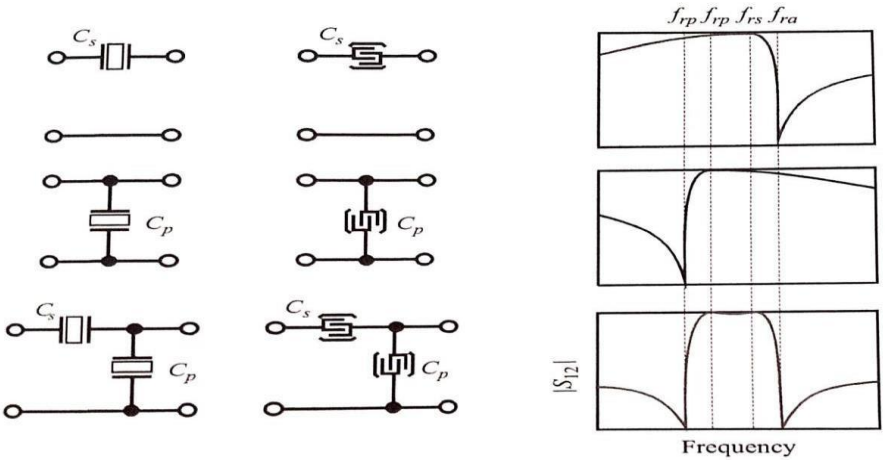


Figure 5.5 S-parameter Vs Frequency



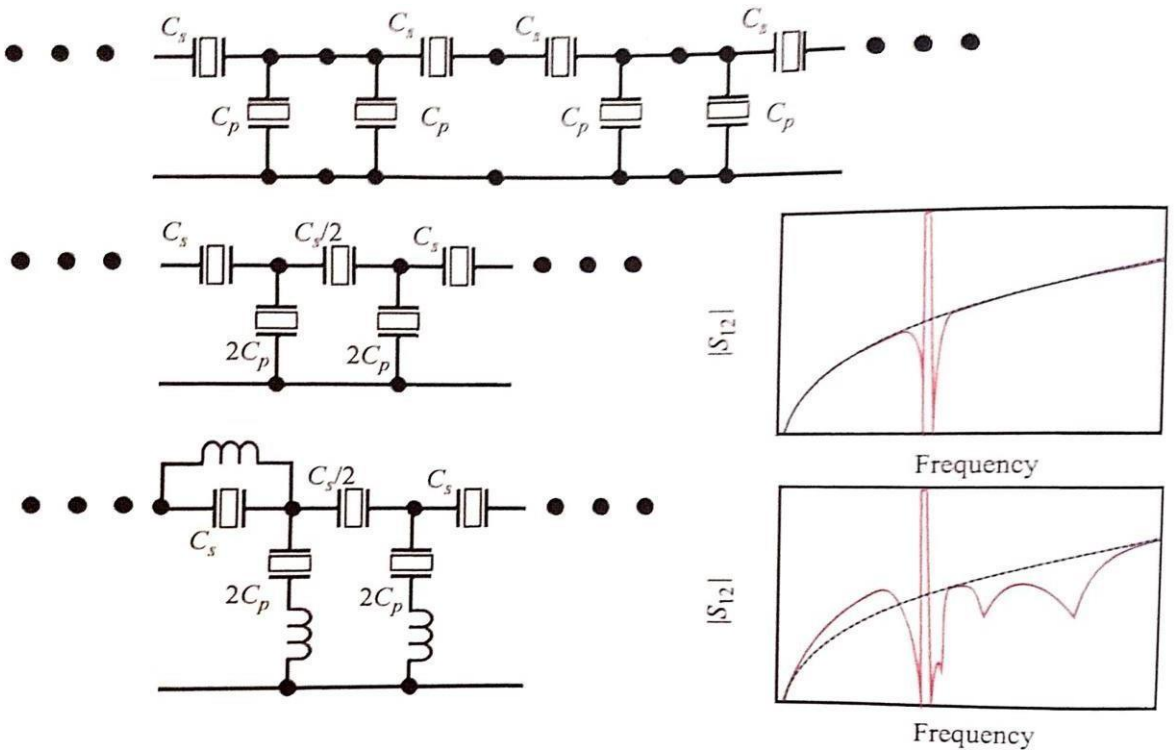


Figure 5.6 Ladder and Lattice filter design

6

SIMULATION AND ANALYSIS

6.1 Device Simulation in COMSOL:

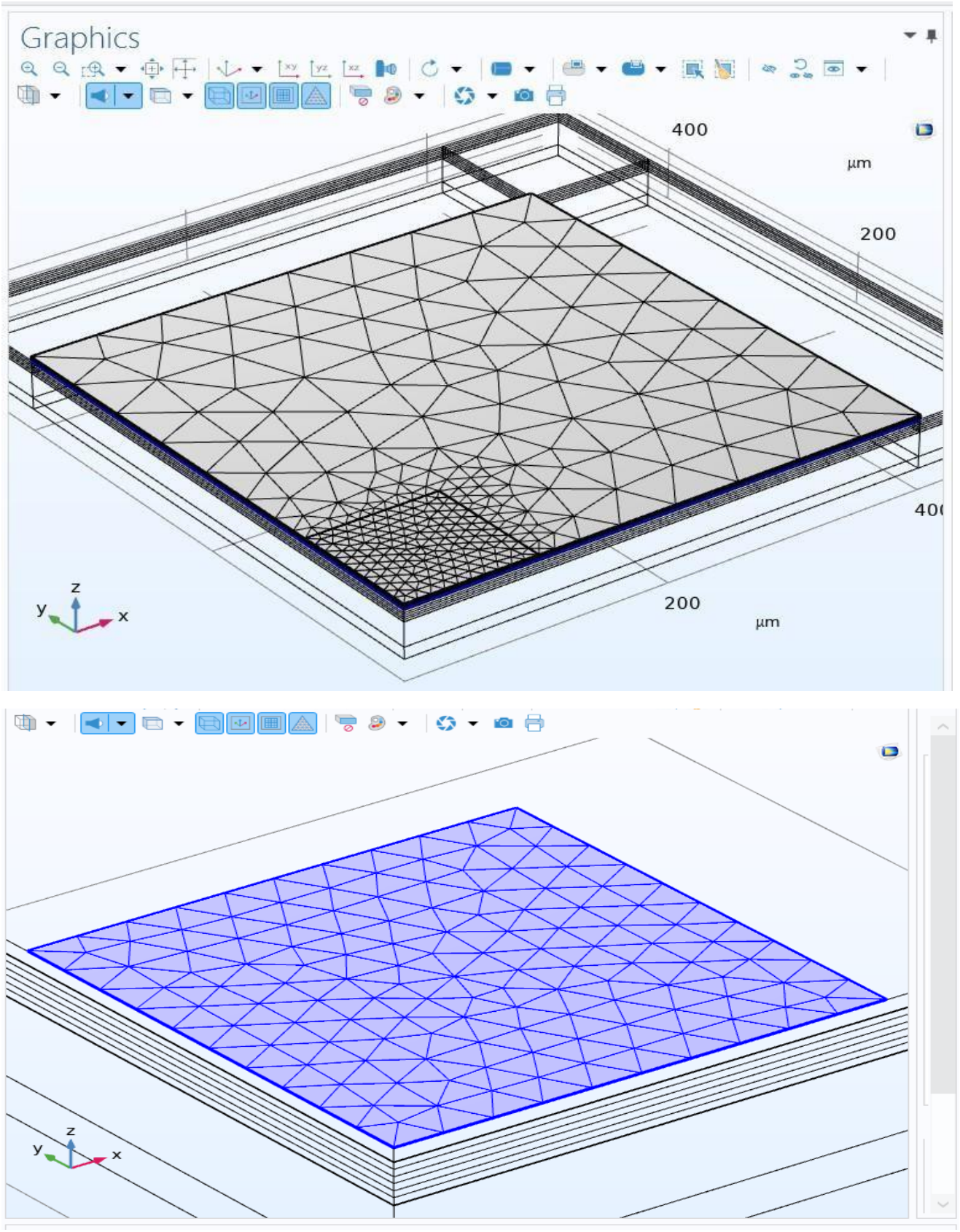


Figure 6.1 3D Model of SMR Structure

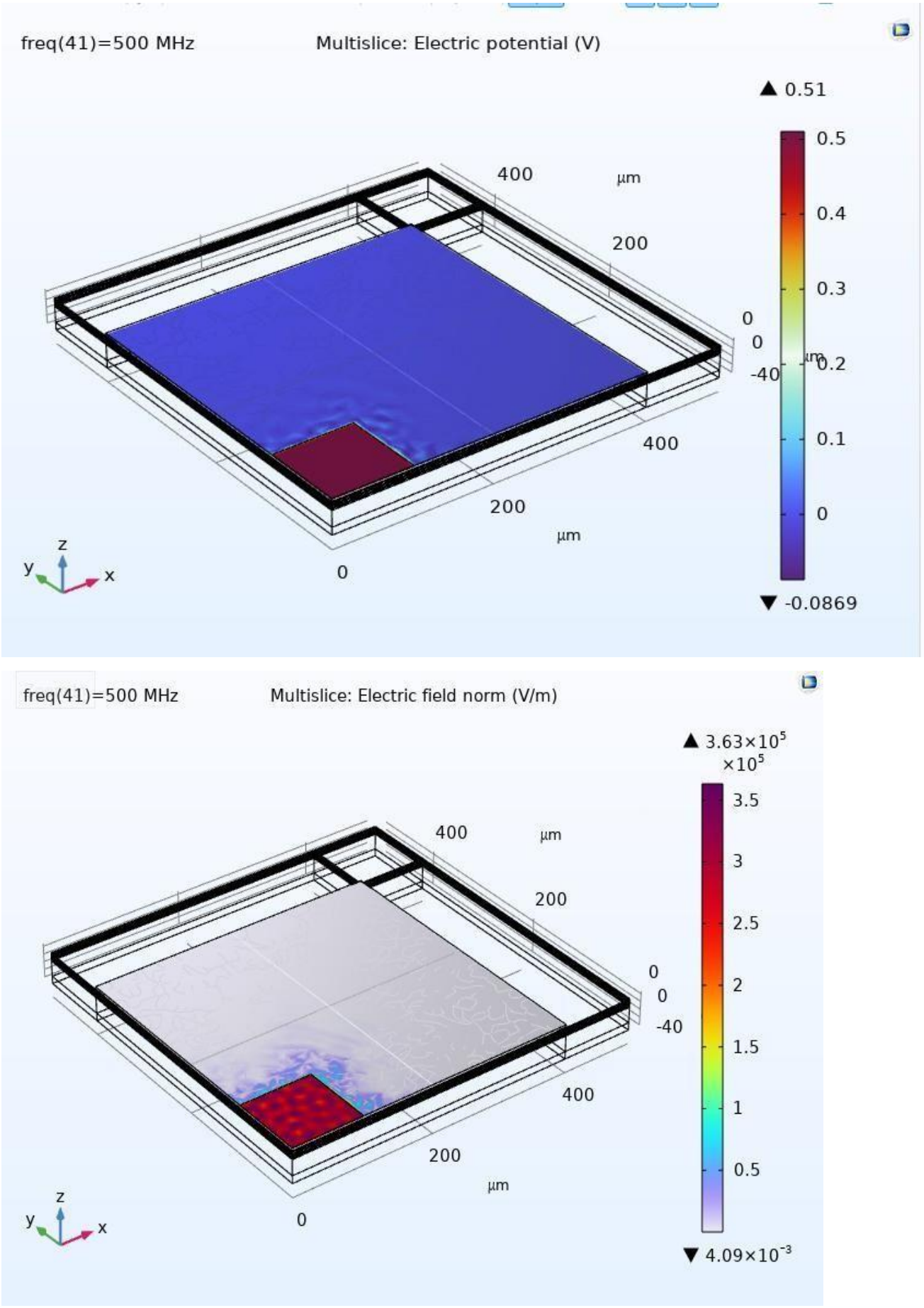
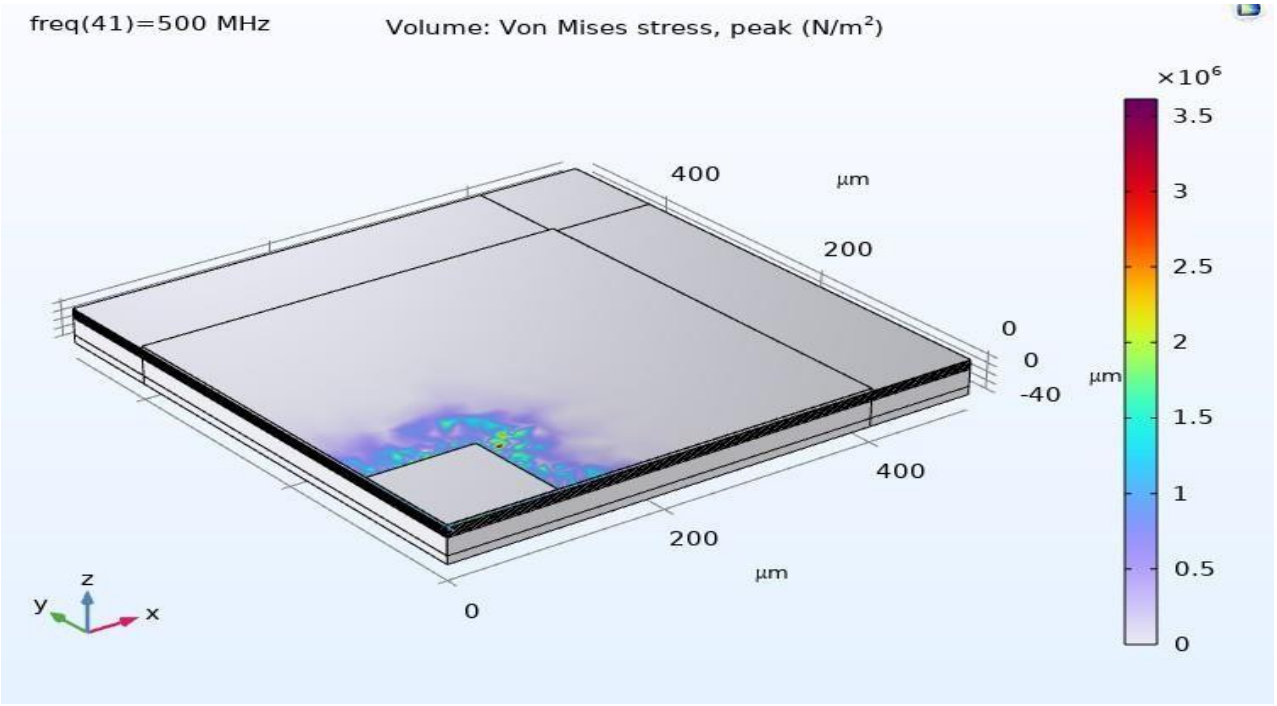
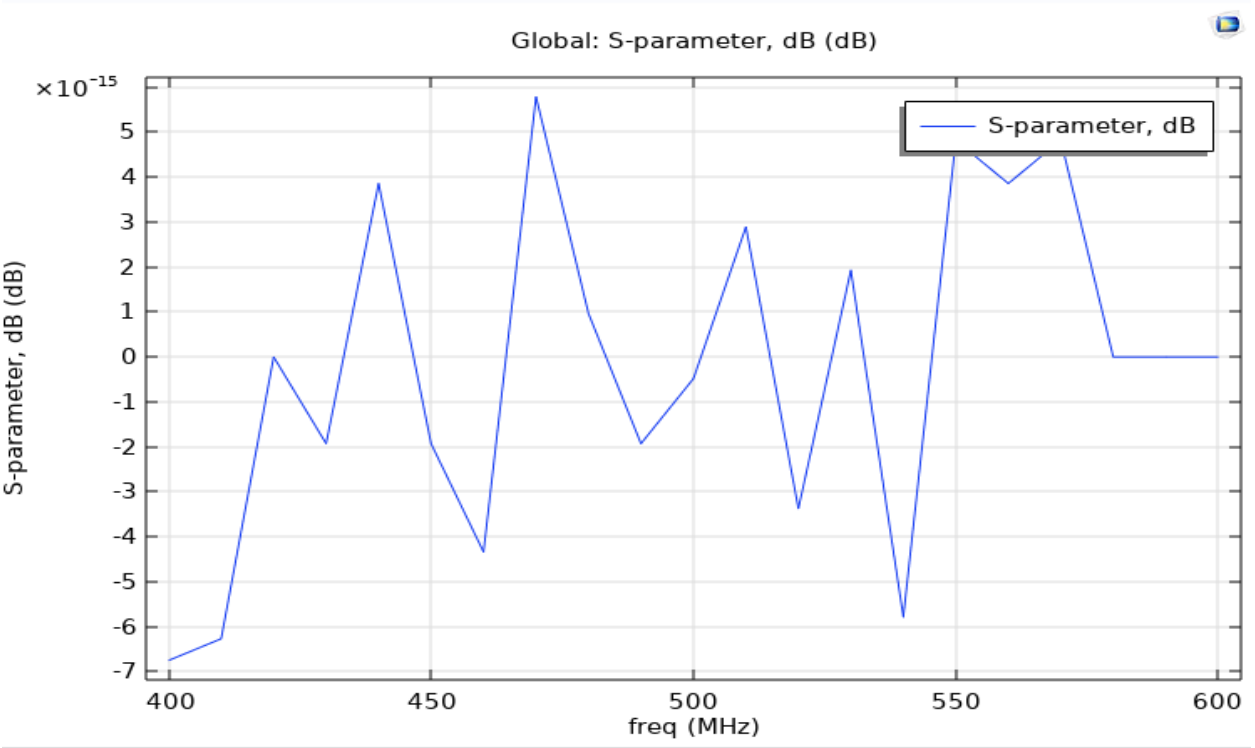
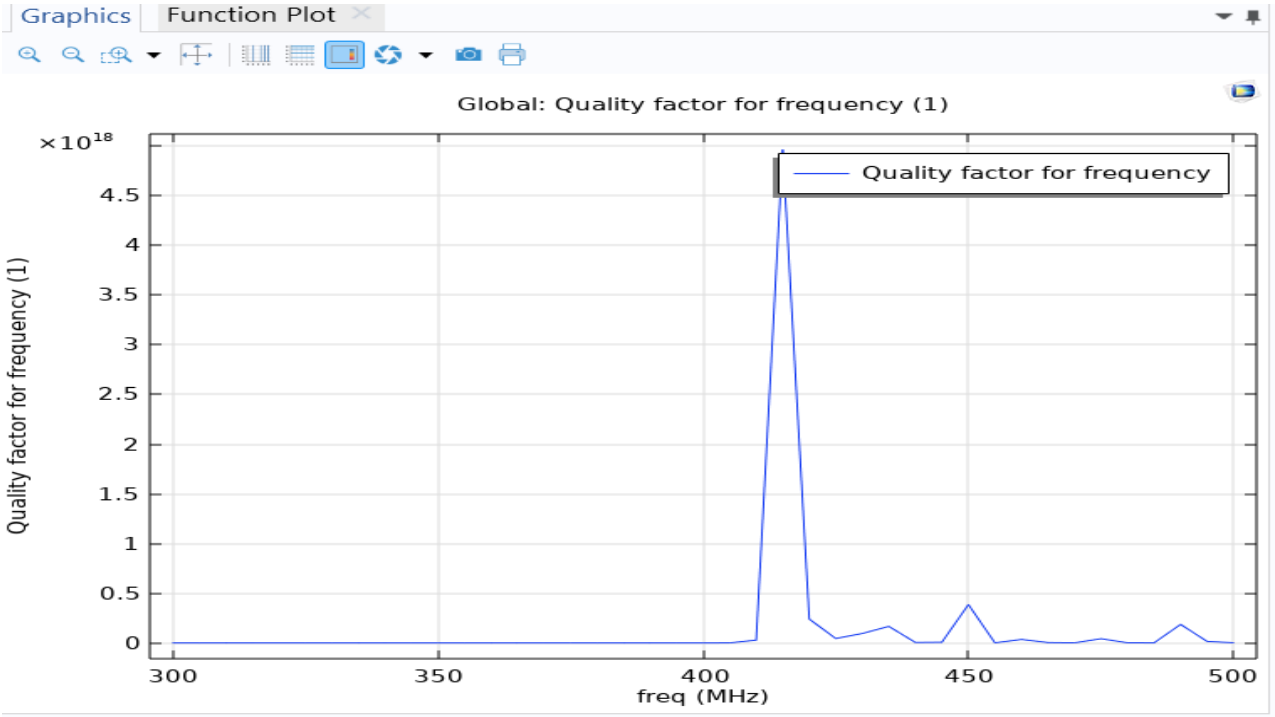


Figure 6.2 Electric potential and Electric field


freq(41)=500 MHz
Volume: Von Mises stress, peak (N/m²)
×10⁶
3.5
3
2.5
2
1.5
1
0.5
0
µm
400
200
0
µm
400
200
0
µm
0
0
-40
z
y
x


Global: S-parameter, dB (dB)
×10⁻¹⁵
S-parameter, dB
S-parameter, dB (dB)
freq (MHz)
400
450
500
550
600
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7



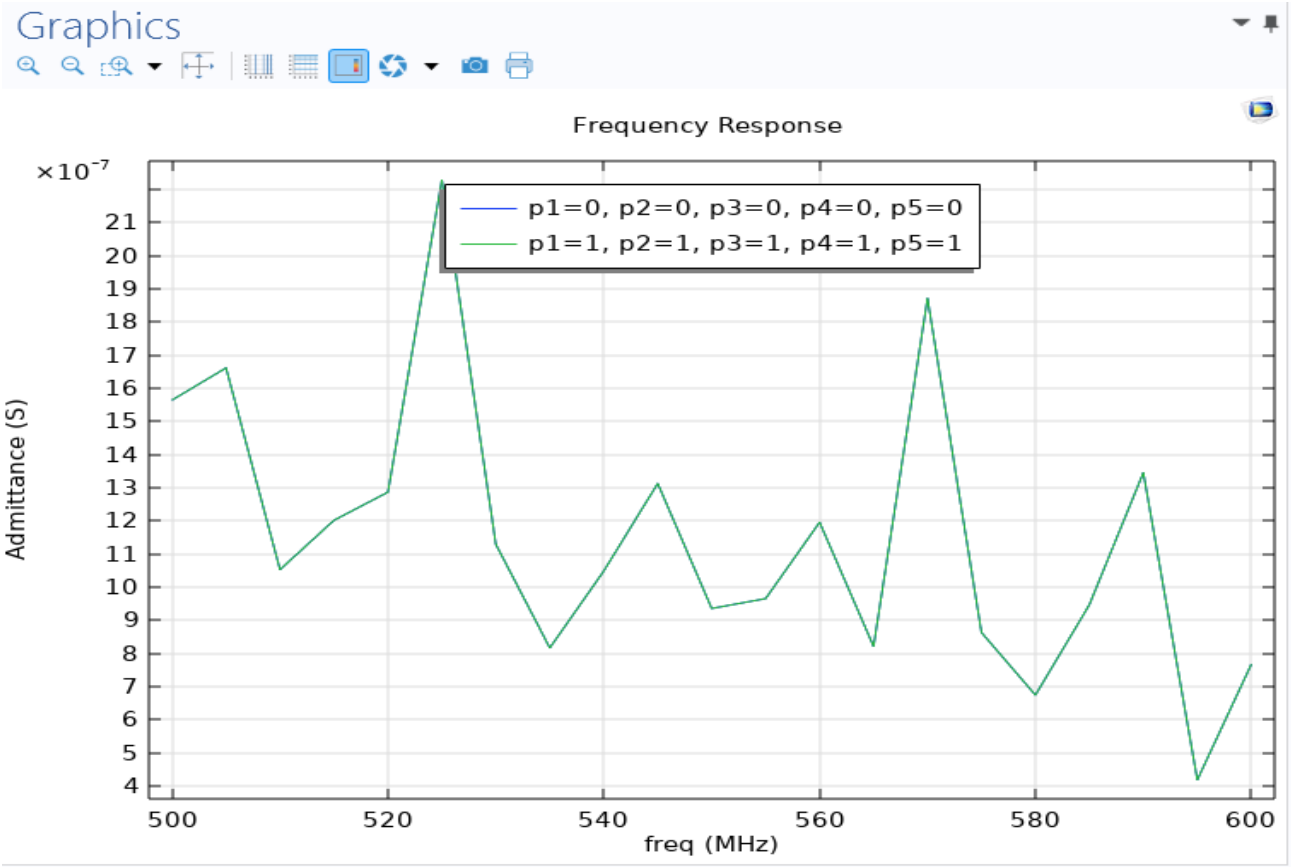
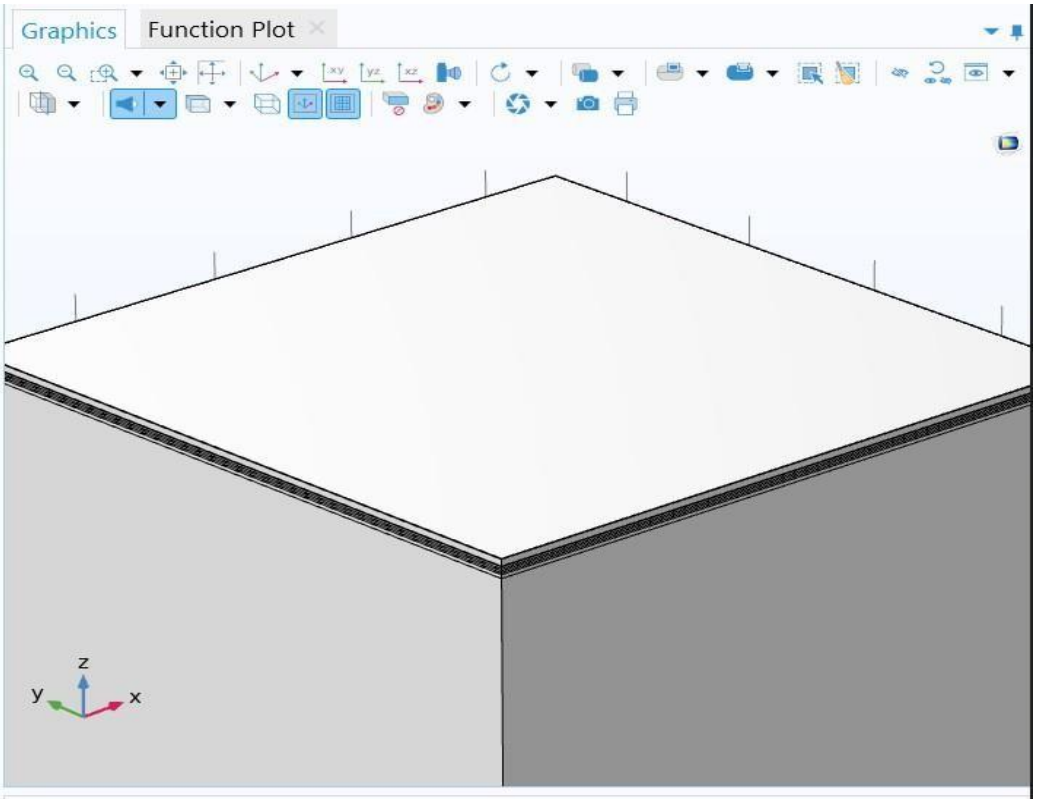


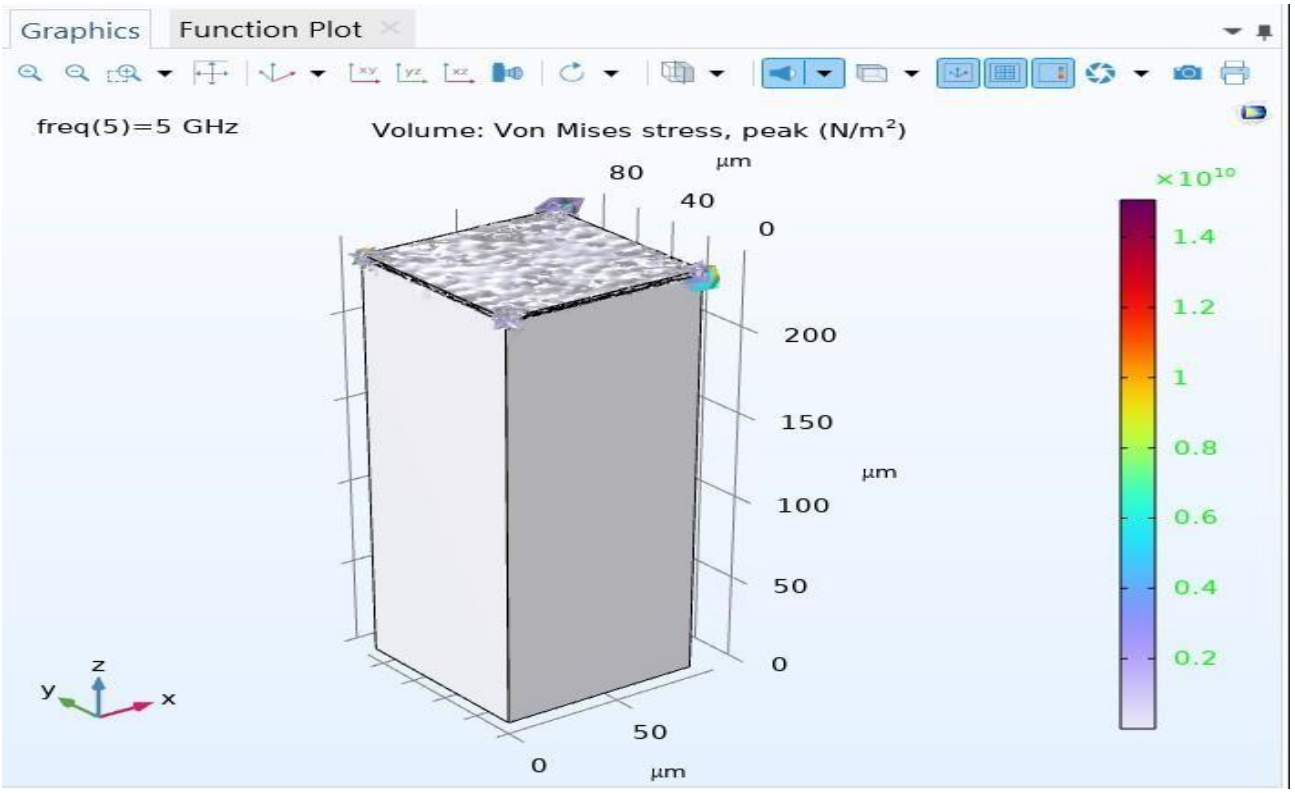
Figure 6.3 S-parameter, Quality factor and Admittance Vs frequency plot

SMR with the following dimensions and material

Sr.No./Layer	Dimensions (um)	Thickness	Material
1.Bottom Si wafer	84.5*84.5	235um	Si
2.Passivation layer	84.5*84.5	500nm	SiO2 Passivation layer
3.Bragg's reflector bottom most	84.5*84.5	240nm	W
4.Bragg's reflector	84.5*84.5	260nm	SiO2
5.Bragg's reflector	84.5*84.5	240nm	W
6.Bragg's reflector	84.5*84.5	260nm	SiO2
7.Bottom electrode	84.5*84.5	100nm	Al
8.piezoelectric layer	84.5*84.5	870nm	AlN
9.Top electrode	84.5*84.5	100nm	Al

Table 6.1 Dimensions and materials for SMR resonator


Graphics
Function Plot
z
y
x


Graphics
Function Plot
freq(5)=5 GHz
Volume: Von Mises stress, peak (N/m²)
µm
80
40
0
200
150
100
50
0
µm
50
0
µm
×10¹⁰
1.4
1.2
1
0.8
0.6
0.4
0.2
z
y
x

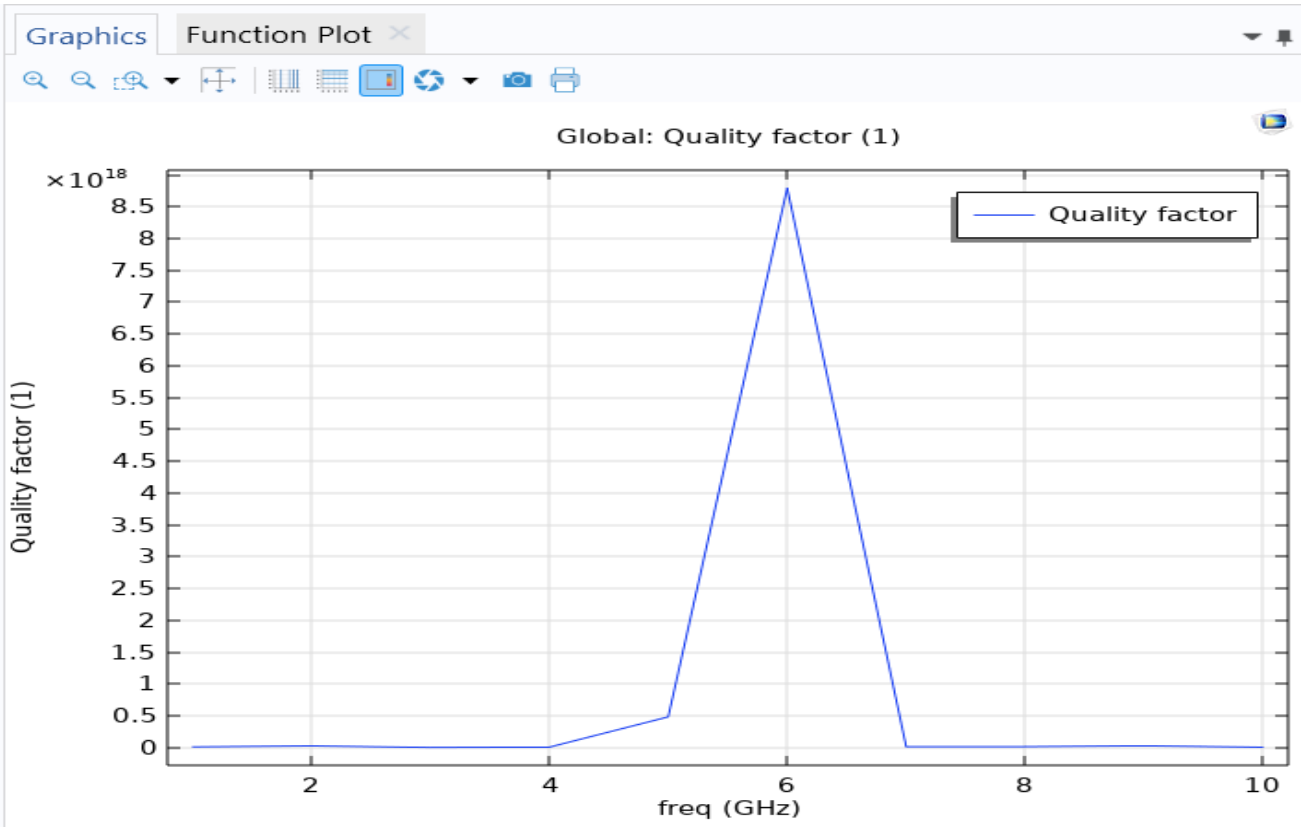
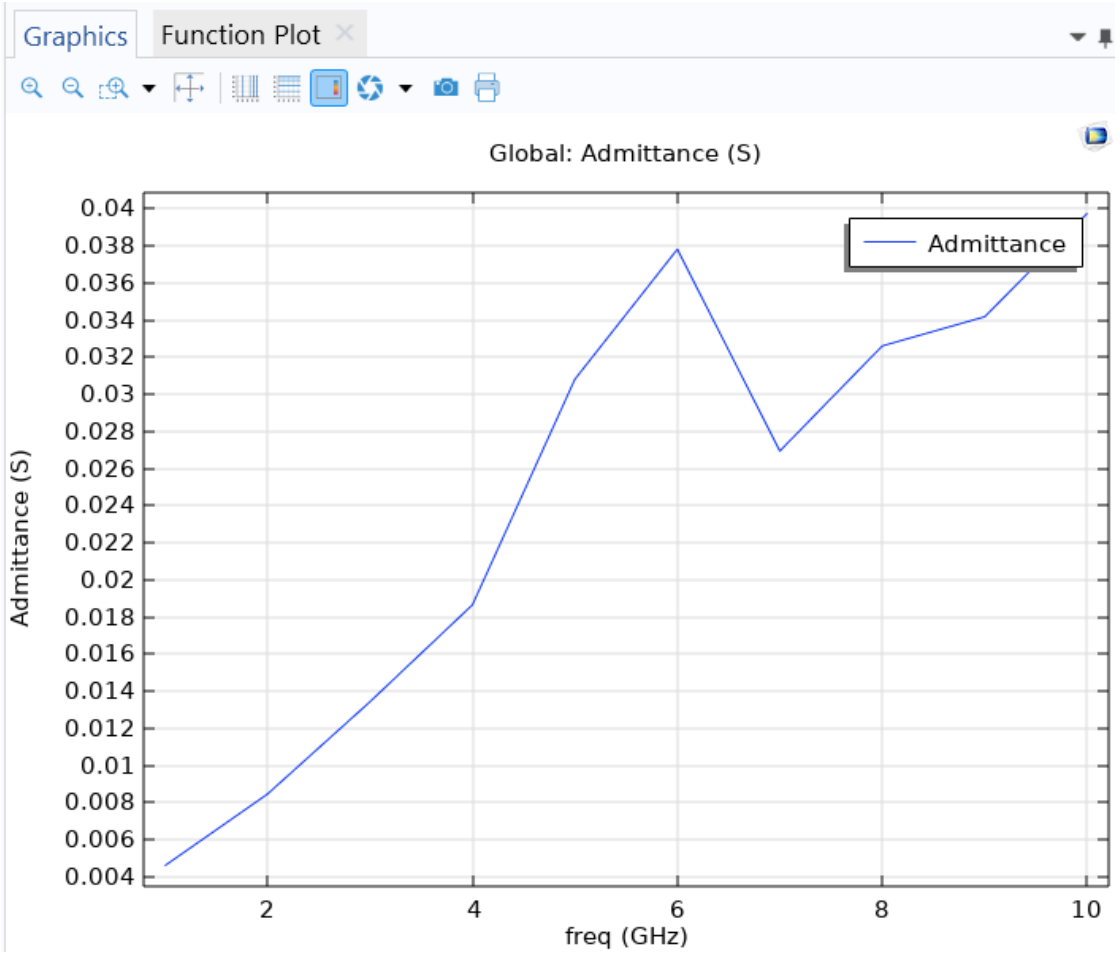


Figure 6.4 Quality factor Vs frequency



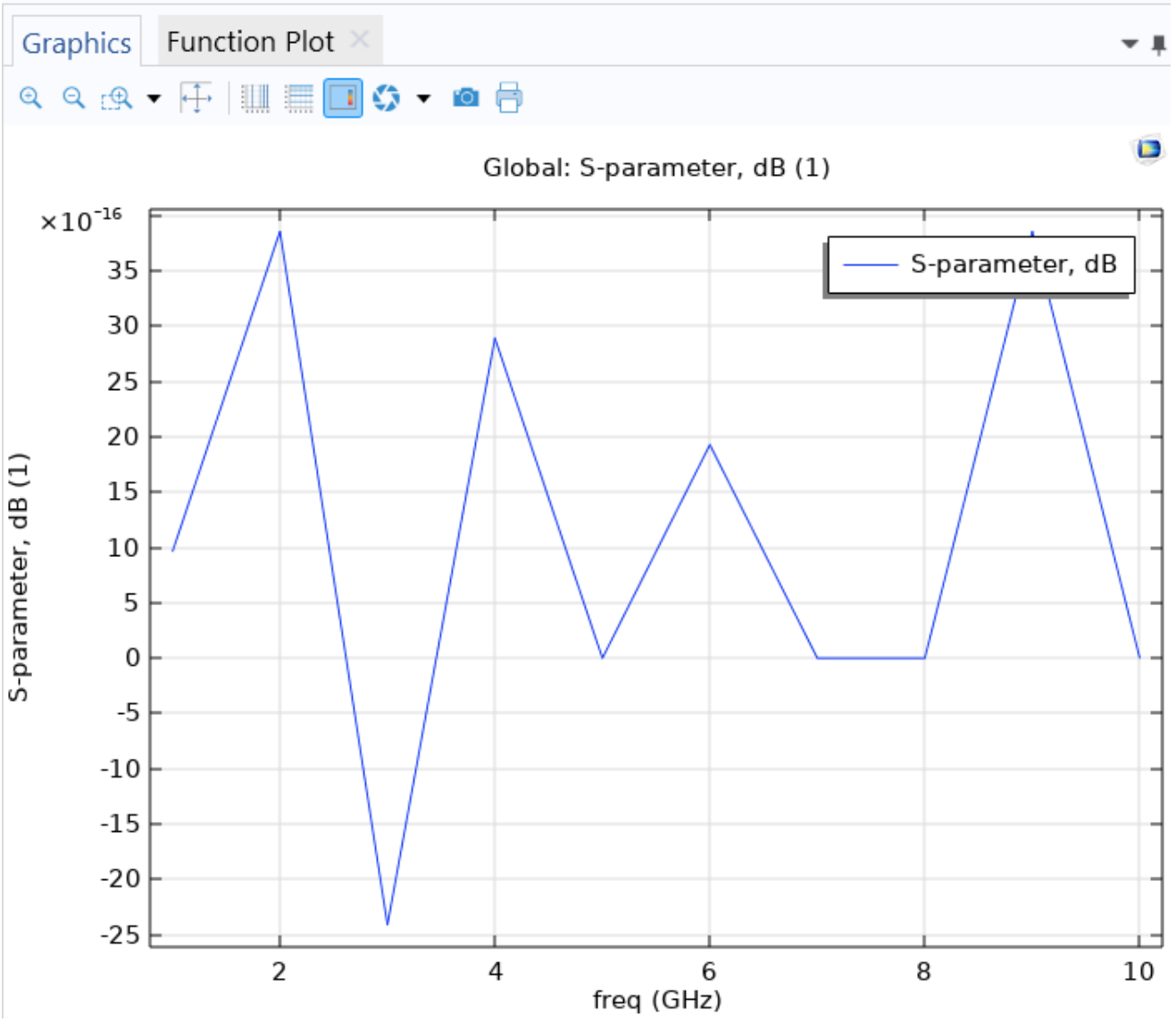


Figure 6.5 Admittance and Scattering parameter Vs frequency

6.2 Circuit Simulation in Cadence virtuoso:

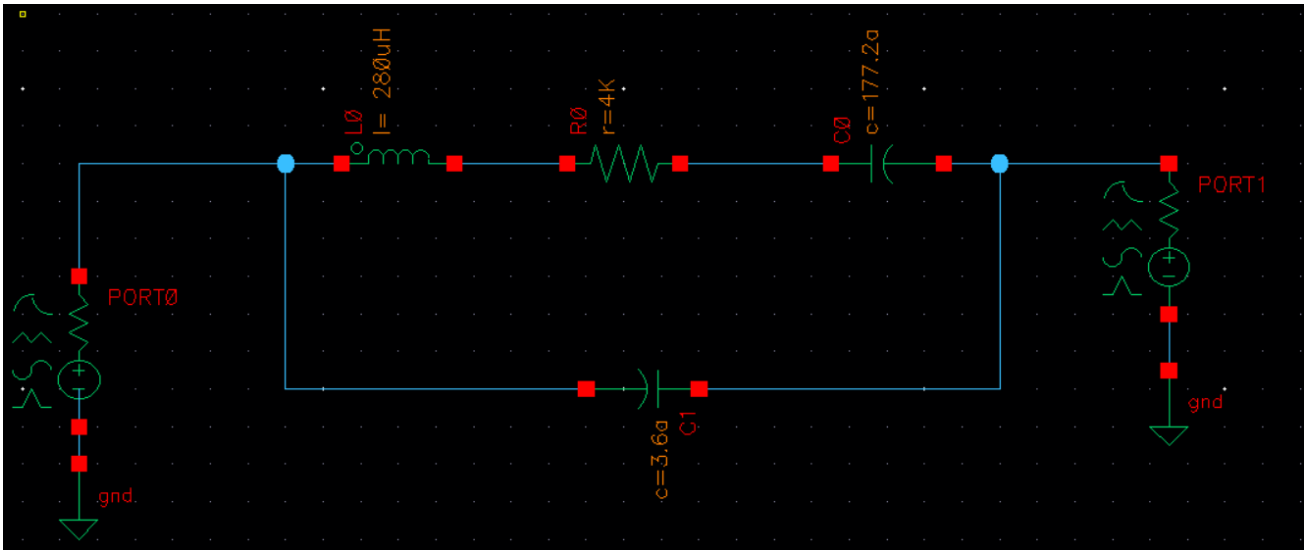


Figure 6.6 Electrical circuit of SMR

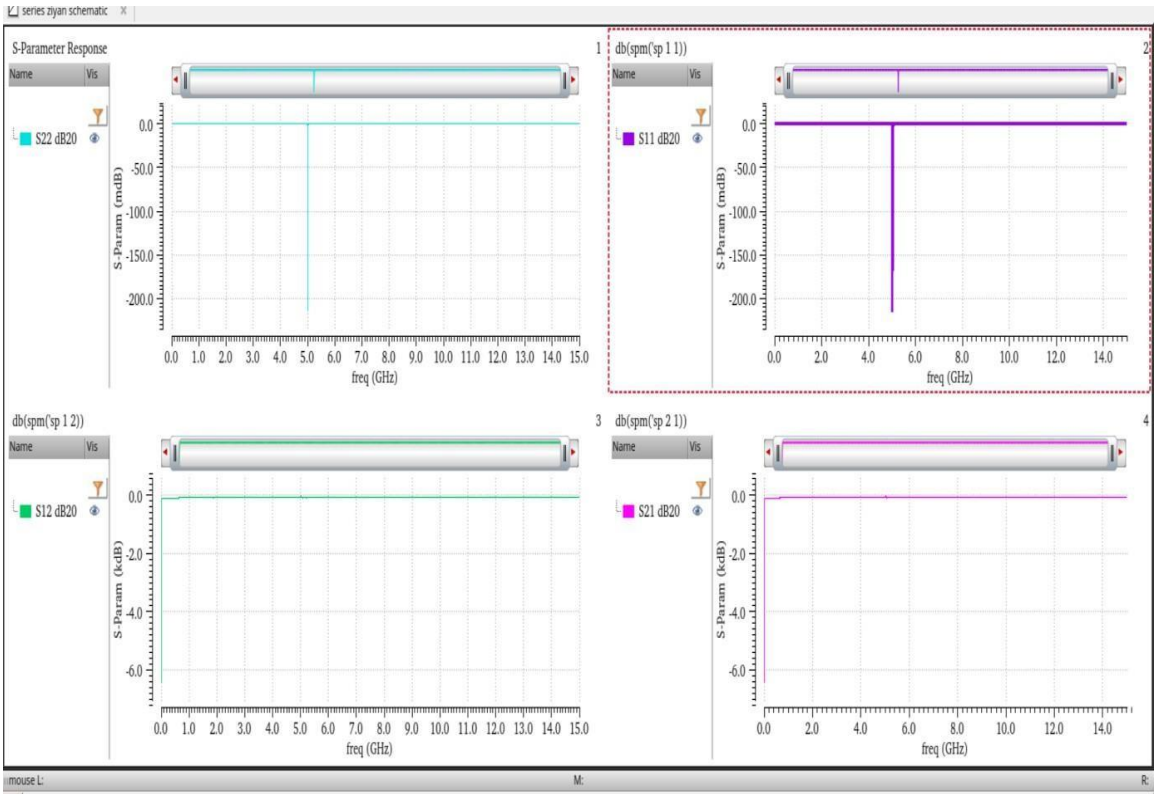


Figure 6.7 S-Parameter Vs Frequency

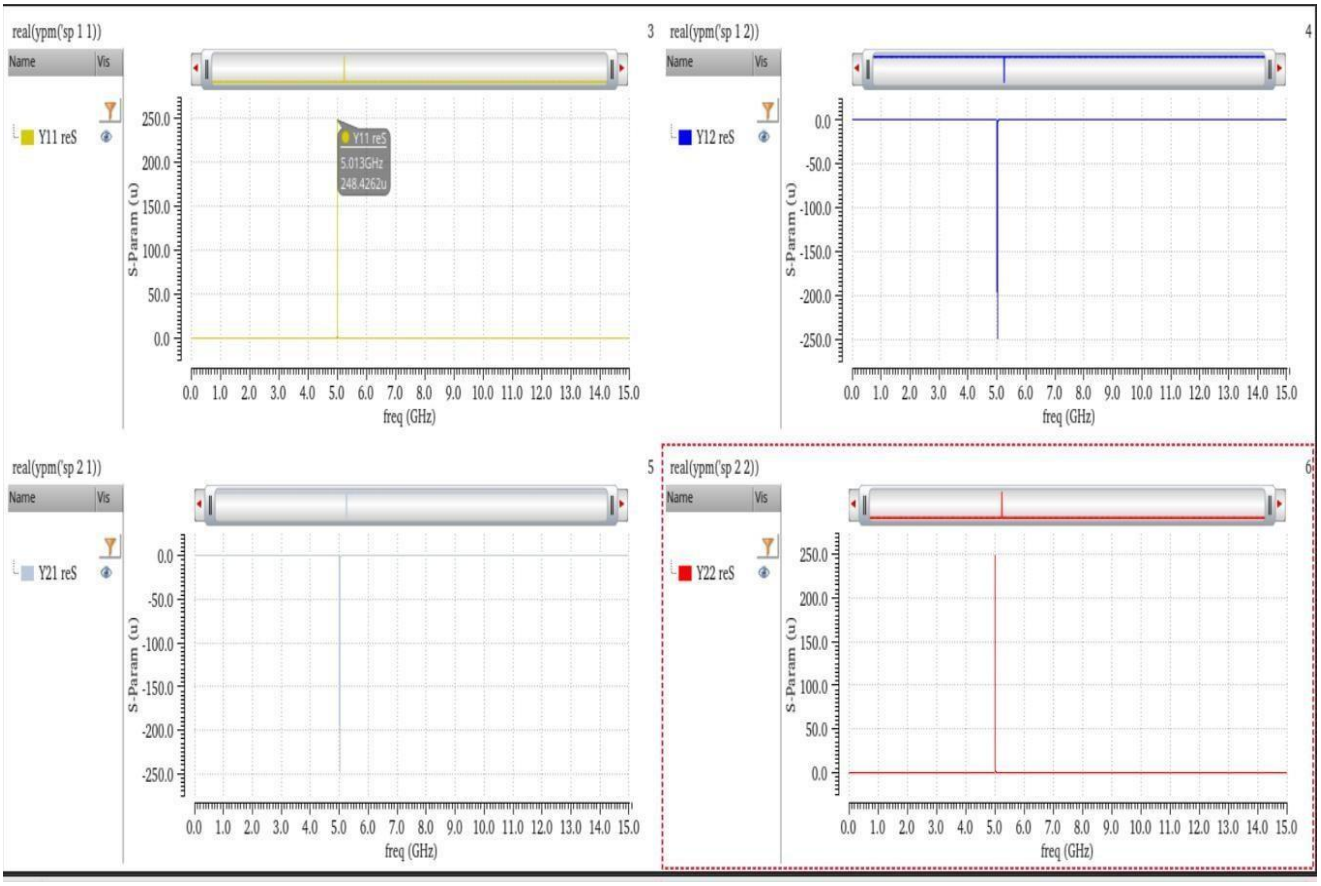


Figure 6.8 Admittance Vs Frequency

7

CONCLUSION & FUTURE SCOPE

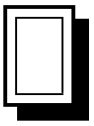
7.1. Conclusion

The use of Solidly Mounted Resonators (SMRs) in filter design represents a significant advancement in RF and microwave communication systems. The key conclusions from the design and implementation of SMR-based filters are:

1. **High Performance:** SMRs provide high Q-factor and low insertion loss, making them suitable for high-frequency applications, particularly in mobile and wireless communication.
2. **Compactness:** The solidly mounted structure eliminates the need for air gaps or suspension,resulting in more robust and compact filters suitable for integration into modern miniaturized electronics.
3. **Thermal Stability:** SMRs exhibit better thermal performance due to their solid mounting on acoustic Bragg reflectors, enhancing stability in varying temperature environments.
4. **Fabrication Compatibility:** The design is compatible with standard MEMS and CMOS processes, facilitating mass production and integration with other IC technologies.

7.2. Future Scope

1. **Integration with CMOS Technology:** Development of monolithic integration of SMR filters with CMOS circuits to create compact System-on-Chip (SoC) solutions.
2. **5G and Beyond Applications:** SMR filters can be tailored for higher frequency bands required in 5G and 6G communication, including millimeter-wave bands.
3. **Material Innovations:** Research into alternative piezoelectric materials (like AlN, ZnO) to further improve electromechanical coupling and frequency range.
4. **Reconfigurable Filters:** Designing tunable or reconfigurable SMR-based filters using varactors or MEMS switches to support multi-band and software-defined radios (SDR).
5. **IoT and Wearable Devices:** Due to their small and high efficiency, SMRs are highly suitable for integration into IoT nodes and wearable electronics.
6. **Improved Modeling and Simulation Tools:** Future work may focus on developing more accurate 3D multi-physics simulation models that account for thermal, mechanical, and electrical effects for better design optimization.
7. **High-Power and Harsh Environment Applications:** Adapting SMR filters for aerospace, defense, and automotive industries where high power handling and environmental resilience are critical.



REFERENCES

[1] Matteo Rinaldi, Chiara Zuniga, Chengjie Zuo and Gianluca Piazza, Philadelphia, “AlN Contour-Mode Resonators for Narrow-Band Filters above 3 GHz”, Department of Electrical and Systems Engineering, University of Pennsylvania, 2009.

[2] RJ Besson. “A new electrode-less resonator design.” In 31st Annual Symposium on Frequency Control, pages 147–152. IEEE, 1977.

[3] Nathanson, H.C.; Newell, W.E.; Wickstrom, R.A.; Davis, J.R., Jr. "The resonant gate Transistor," Electron Devices, IEEE Transactions on Mar 1967.
DOI: 10.1109/T-ED.1967.15912.

[4] Frank D. Bannon, John R. Clark, Clark T.-C. Nguyen, "High frequency micromechanical IF filters", Technical Digest, 1996 IEEE Electron Devices Meeting, San Francisco, CA, Dec. 8-11, 1996, pp. 773–776.

[5] G. Piazza, P. J. Stephanou, and A. P. Pisano, “Piezoelectric aluminum nitride vibrating contour-mode MEMS resonator,” J. Microelectromech. Syst., vol. 15, no. 6, pp. 1406–1128, Dec 2006.

[6] Vivek Harshey, Amol Morankar, Dr. R.M. Patrikar “MEMS Resonator for RF Applications”, 2011.

[7] Lakin K.M., McCarron K.T., and Rose R.E. “Solidly mounted resonators and filters”. Proceedings of IEEE Ultrasonics Symposium; Seattle, USA, Nov. 1995, pp. 905–908.

[8] “Fundamentals of Piezoelectricity” by R.S. Dahiya and M. Valle.

[9] Prasanna P. Deshpande, Rajesh S. Pandel and Rajendra M. Patrikar, “Fabrication and characterization of zinc oxide piezoelectric MEMS resonator”;/doi.org/10.1007/s00542-019-04509-w, 2019.

[10] Tristan O. Rocheleau, Thura Lin Naing, Zeying Ren, and Clark T.-C. Nguyen, “ACOUSTIC WHISPERING GALLERY MODE RESONATOR WITH Q > 109,000 AT 515MHz”; University of California, Berkeley, USA, 978-1-4673-0325-5/12, IEEE, 2012.

[11] Manjula Sutagundar, B.G. Sheeparamatti, D.S. Jangamshetti,
“Research Issues in MEMS Resonators”,
Dept. of Electronics and Commn., Research Inventy: International Journal of Engineering And Science Vol. 4, Issue 8 (August 2014).

[12] Reza Abdolvand, Behraad Bahreyni, Joshua E.-Y. Lee and Frederic Nabki;
“Micromachined Resonators: A Review”; doi:10.3390/mi7090160, 2016.

[13] H. Campanella Pineda, Thin-film bulk acoustic wave resonators-FBAR: fabrication, heterogeneous integration with CMOS technologies and sensor applications. Universitat Autonoma de Barcelona, 2008.

[14] Bradley, P. et al. “A Film acoustic bulk resonator (SMR) duplexer for USPCS Handset Applications”, IEEE MTT-S, pp.367–370, 2001.

[15] Shirakawa, A. A. Pham, J-M. Jarry, P. Kerherve, E. Dumont, F. David, J-B. Cathelin, A.“A High Isolation and High Selectivity Ladder-Lattice BAW-SMR Filter”, 36th European Microwave Conference, 2006, Manchester, UK, pp. 905 – 908, 10-15 September.